RHIC Physics:
Adventures at the Highest Temperatures Created in the Laboratory

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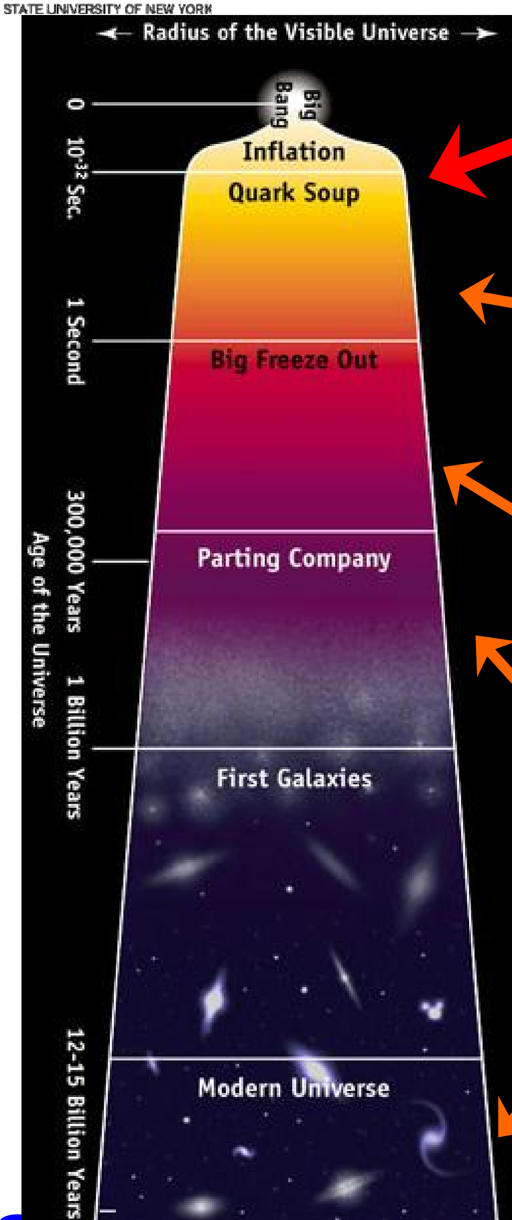
Evolution of the Universe



Reheating Matter

T… nd!!!

Standard Model (N/P) P…

Too hot for nuclei to bin…

Nuclear/Particle (N/P)

…ynthesis builds

Nucle… Force…Nucle…

…) Physics

…e

…/General Relativity

Quark-

- Collisions of "Large" nuclei convert beam energy to temperatures above 200 MeV or 1,500,000,000,000 K
  - ~100,000 times higher temperature than the center of our sun.
- "Large" as compared to mean-free path of produced particles.

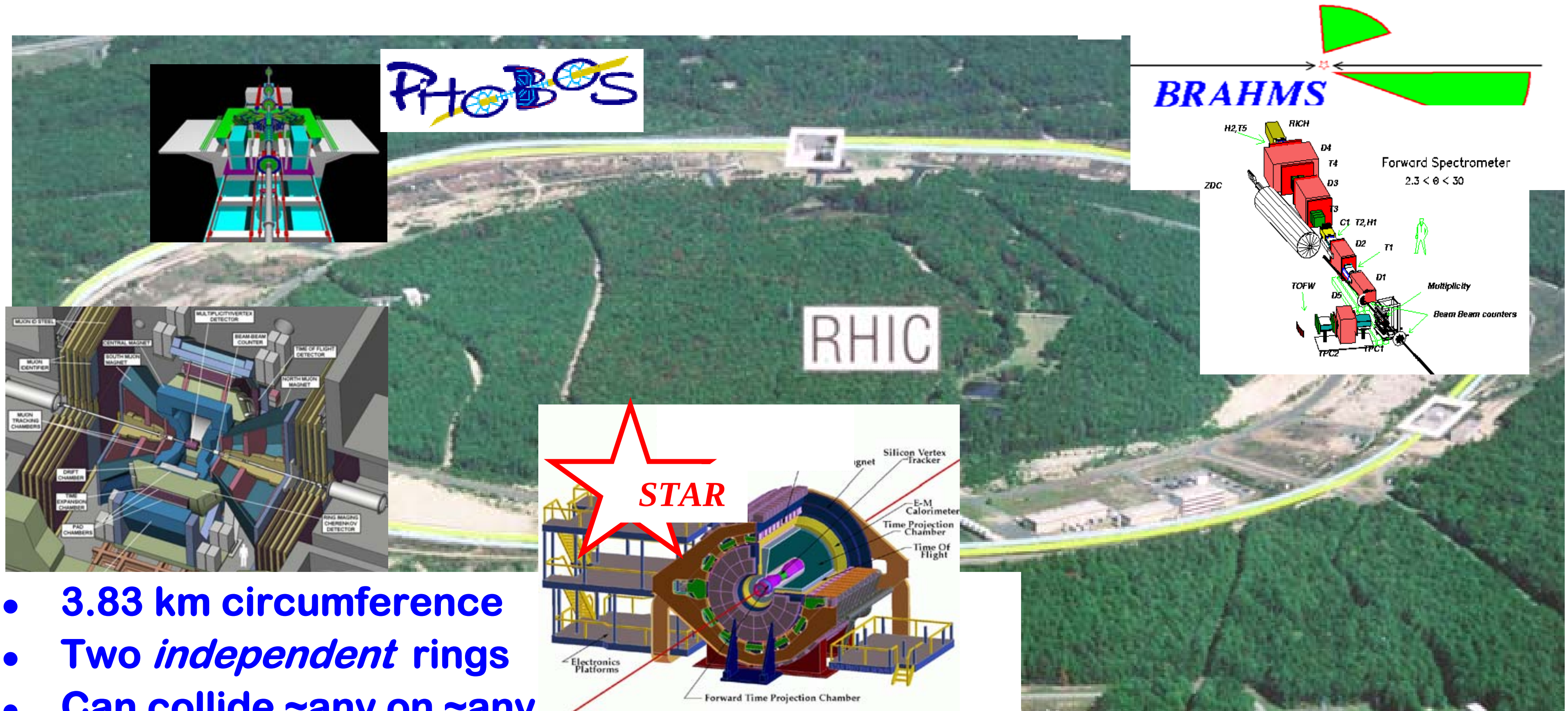
Stars convert gravitational energy to temperature.

They "replay" and finish nucleosynthesis

~15,000,000 K in the center of our sun.

Solid
Liquid
Gas

RHIC's Experiments



- **3.83 km circumference**
- **Two *independent* rings**
- **Can collide ~any on ~any**
  - **AuAu, pp, dAu, CuCu**
- **Top Center-of-Mass Energy:**
  - ➔ **500 GeV for p-p; 200 GeV/nucleon for Au-Au**
- **Luminosity**
  - **Au-Au: 2×10^{26} cm^{-2} s^{-1}; p-p : 2×10^{32} cm^{-2} s^{-1}**

Outline of Lecture

- Are we in the Ballpark?
  - Energy Density
  - Chemical Equilibrium
  - Kinetic Equilibrium
- Is There a There There?
  - The Medium & The Probe
  - High Pt Suppression
  - Control Experiments: dAu, γ_{direct}
- What is It Like?
  - Azimuthally Anisotropic Flow
  - Hydrodynamic Limit
  - Recombination
- Hot new results you'll see <u>This Week</u> (shopping list)
  - Charm Spectral Modification
  - J/Y suppression(?)
  - Volcano Jet Shapes.
  - Direct Photons

The Ballpark

- Lattice QCD tells us that we should look for:
  - $\varepsilon > 1$ GeV/fm^3
    - Lower bounds on ε can be established by a CAREFUL analysis of transverse energy and multiplicity production
  - T > 170 MeV
    - Random motion (T) can be separated from collective motion so as to yield a measure of the final state temperature.
    - Particle abundances can be compared to simple chemical equilibrium calculations to establish a final state temperature (necessary a lower bound to initial state temperature).
- Neither of these measures is sufficient to establish QGP formation, however both are necessary and thereby tell us whether we are "in the ballpark".

ε: Ridiculous to Sublime

- **Energy Density defined as** $\varepsilon \equiv \dfrac{Energy}{Volume}$ **(in P=0 frame)**

- **Let's calculate the Mass overlap Energy:**

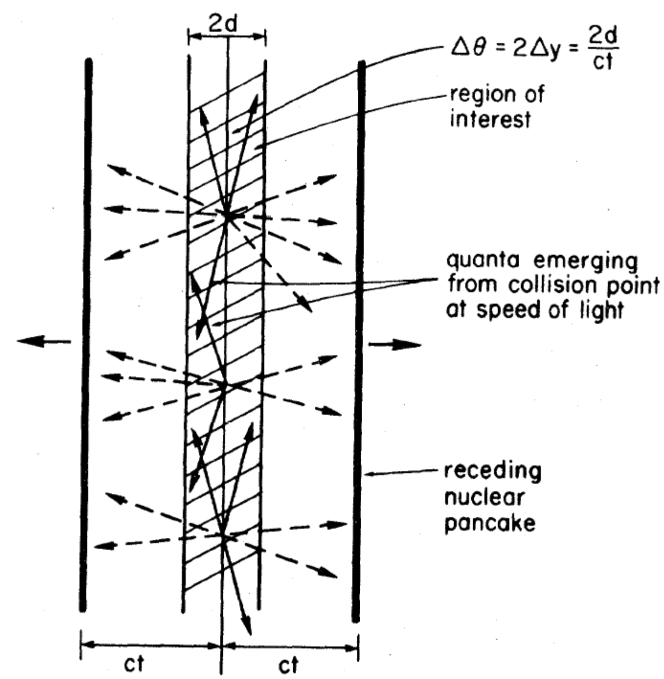
$$\langle \varepsilon \rangle = 2\rho_0 \gamma^2 = 3150 \frac{GeV}{fm^3} \qquad \rho_0 = 0.14 \frac{GeV}{fm^3} ; \gamma_{RHIC} = 106$$

Meaningless Drivel

- **Bjorken Energy Density Formula:**

$$\langle \varepsilon_{BJ}(t_{form}) \rangle = \frac{1}{t_{form} A} \frac{dE_T(t_{form})}{dy}$$

Assumed **Measured**



Initial Energy density

Summary:

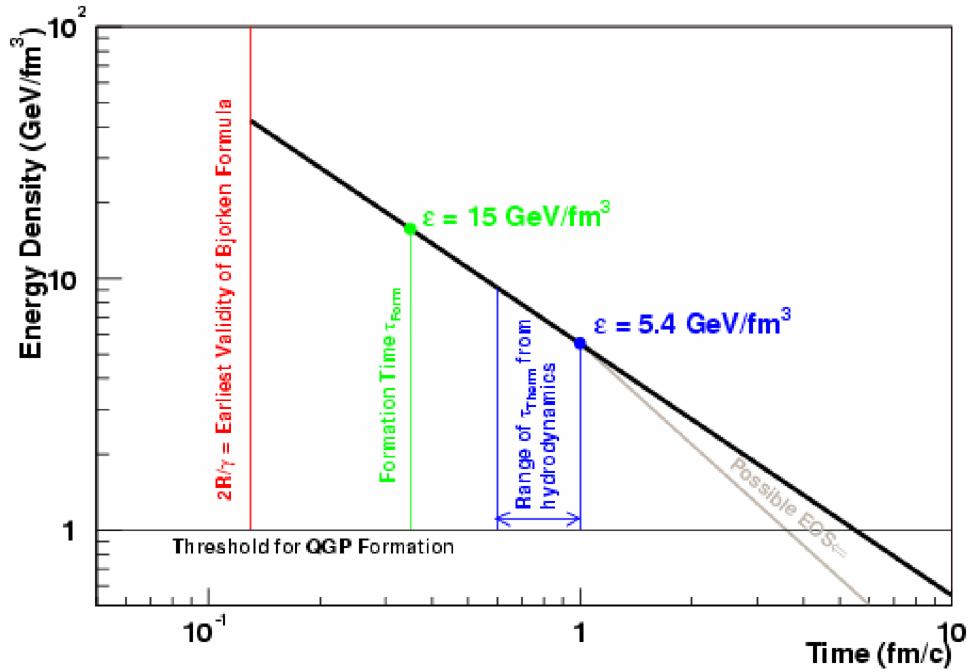
- **Two values of τ_0:**
  - $\tau_{form} = \hbar / \langle m_T \rangle (\tau_{form})$
    $\leq \hbar / \langle m_T \rangle^{final} = 0.35$ fm/c
  - τ_{therm} ≤ 1 fm/c (hydro)

- **We derive conservative *lower limits* on the energy density at formation and thermalization**

  ε(form) > 15 GeV/fm^3

  ε(therm) > 5.4 GeV/fm^3

  in central Au+Au collision at 200 GeV



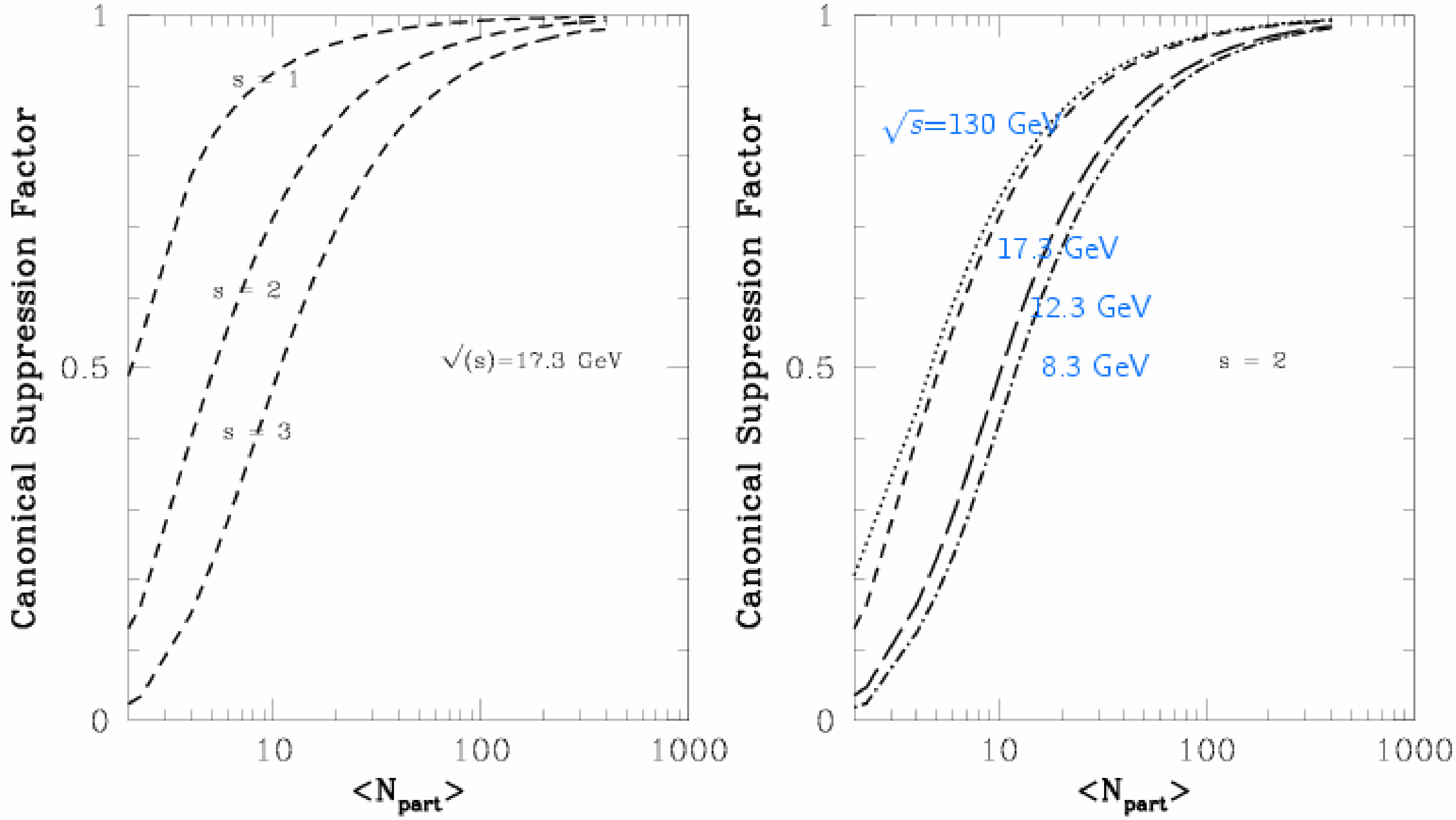
These values are well in excess of ~1 GeV/fm3 obtained in lattice QCD as the energy density needed to form a deconfined phase.

Thermal Equilibrium

- We'll consider two aspects of thermal predictions:
  - Chemical Equilibrium
    - Are all particle species produced at the right relative abundances?
  - Kinetic Equilibrium
    - Energetic sconsistent with common temperature plus flow velocity?
- Choose appropriate statistical ensemble:
  - Grand Canonical Ensemble: In a large system with many produced particles we can implement conservation laws in an averaged sense via appropriate chemical potentials.
  - Canonical Ensemble: in a small system, conservation laws must be implemented on an EVENT-BY-EVENT basis. This makes for a severe restriction of available phase space resulting in the so-called "Canonical Suppression."
  - Where is canonical required:
    - low energy HI collisions.
    - high energy e+e- or hh collisions
    - Peripheral high energy HI collisions

Canonical Suppression

Tounsi and Redlich, hep-ph/0211159



for $N_{part} \geq 60$ Grand Canonical ok to better 10%

Canonical Suppression is likely the driving force behind "strangeness enhancement"

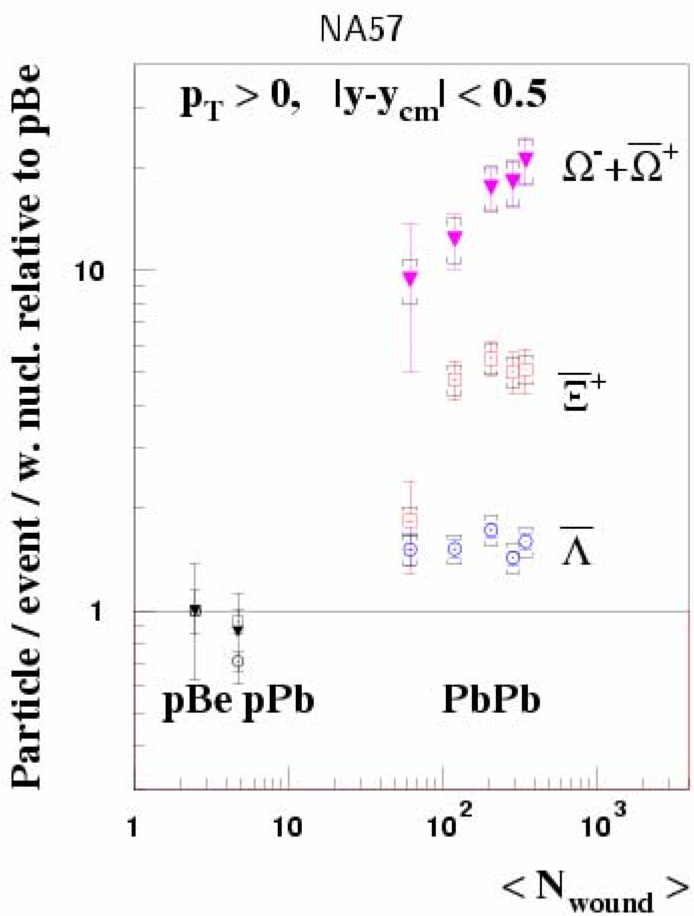
Thermal yields

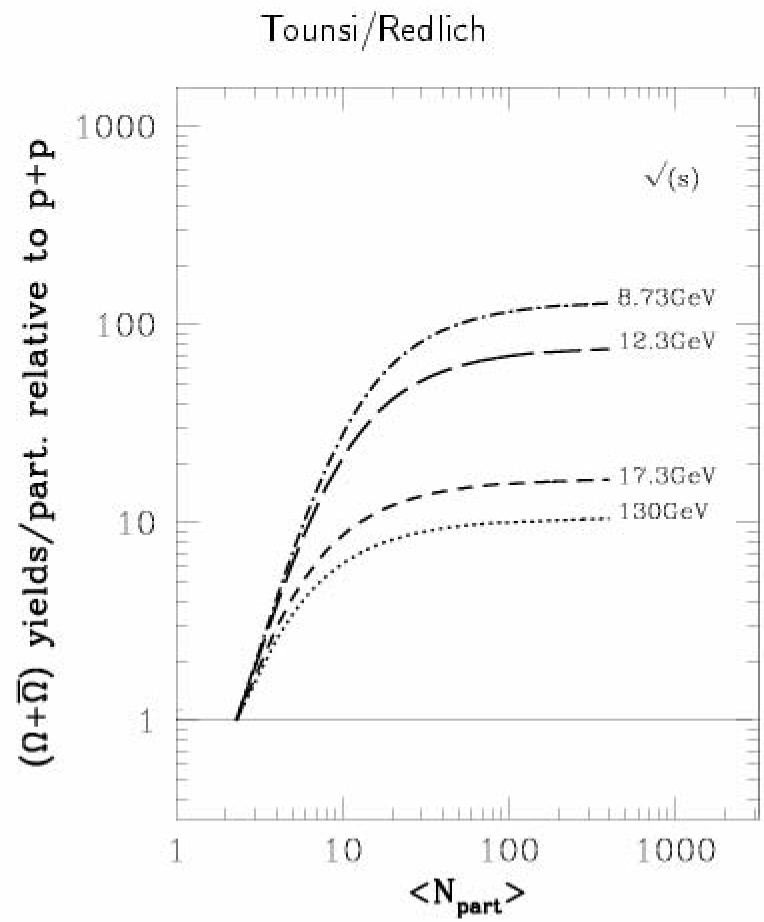
- The formula for the number density of all species:

$$n_i^0 = \frac{g_i}{2\pi^2}\int \frac{p^2 dp}{e^{\left(E-\mu_B B_i-\mu_s S_i-\mu_3 I^3\right)/T} \pm 1}$$

  here g_i is the degeneracy
  $E^2=p^2+m^2$
  μ_B, μ_S, μ_3 are baryon, strangeness, and isospin chemical potentials respectively.
- Given the temperature and all m, on determines the equilibrium number densities of all various species.
- The ratios of produced particle yields between various species can be fitted to determine T, μ.

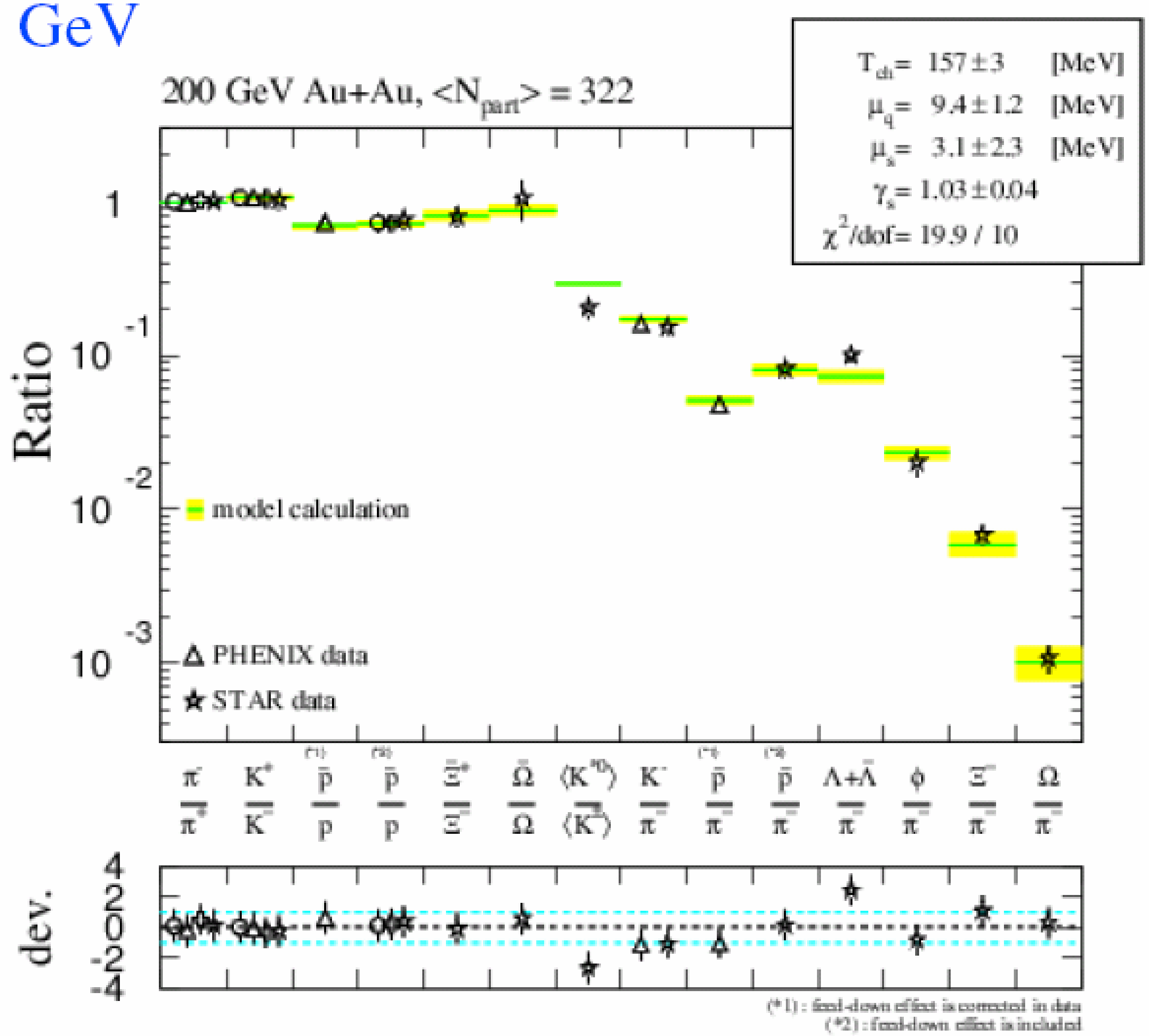
Strangeness Enhancement in 158 A GeV/c Pb + Pb Collisions





Ω enhancement central ok. but doesn't flatten at $N_{part} = 100$

200 GeV



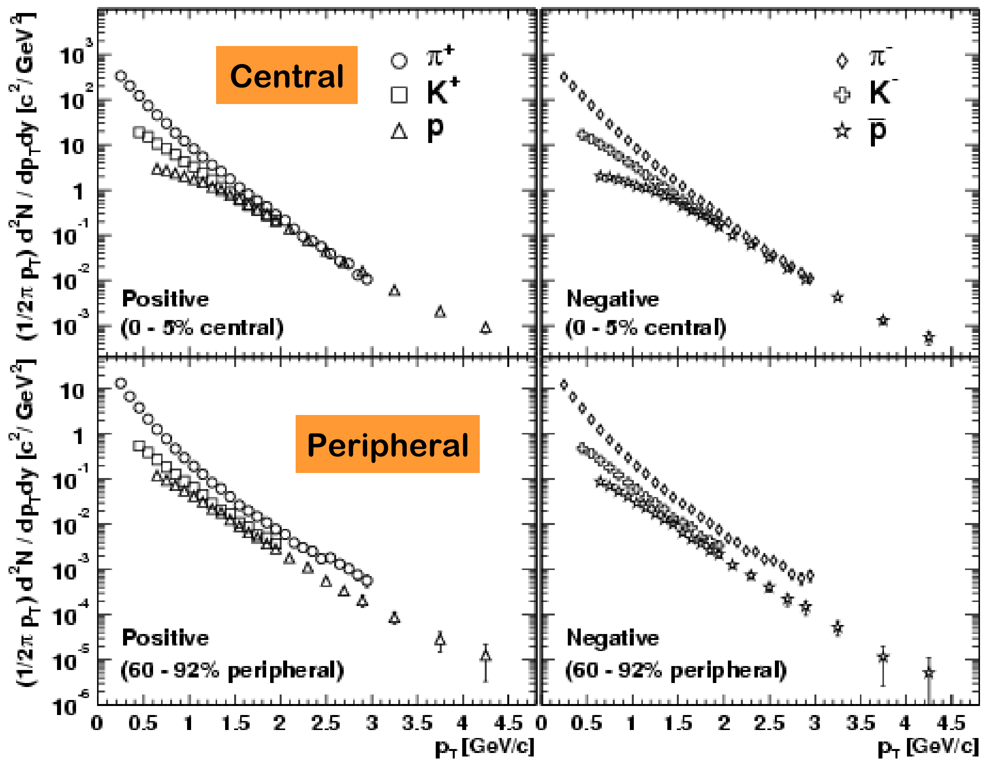
200 GeV Au+Au, <N_part> = 322
T_ch = 157±3 [MeV]
μ_q = 9.4±1.2 [MeV]
μ_s = 3.1±2.3 [MeV]
γ_s = 1.03±0.04
χ²/dof = 19.9 / 10
Ratio
model calculation
PHENIX data
STAR data
dev.
(*1) : feed-down effect is corrected in data
(*2) : feed-down effect is included

Flow I (parameterized)

- For any interacting system of particles expanding into vacuum, flow is a natural consequence.
  - During the cascade process, one naturally develops an ordering of particles with the highest common underlying velocity at the outer edge.
- This motion complicates the interpretation of the momentum of particles as compared to their temperature and should be subtracted.
  - Although 1st principles calculations of fluid dynamics are the higher goal, simple parameterizations are nonetheless instructive.
- Hadrons are released in the final stages of the collision and therefore measure **"FREEZE-OUT"**

Singles Spectra

- **Peripheral:**
  - Pions are concave due to feeddown.
  - K,p are exponential.
  - Yields are MASS ORDERED.
- **Central:**
  - Pions still concave.
  - K exponential.
  - p flattened at left
  - Mass ordered wrong (p passes pi !!!)



Underlying collective VELOCITIES impart more momentum to heavier species consistent with the basic trends

Blast Wave

- **Let's consider a Thermal Boltzmann Source:**

$$\frac{d^3N}{dp^3} \propto e^{-E/T}; E\frac{d^3N}{dp^3} = \frac{d^3N}{m_T dm_T d\phi dy} \propto Ee^{-E/T} = m_T \cosh(y) e^{-m_T \cosh(y)/T}$$

- **If this source is boosted radially with a velocity β_{boost} and evaluated at y=0:**

$$\frac{1}{m_T}\frac{dN}{dm_T} \propto m_T I_0\left(\frac{p_T \sinh(\rho)}{T}\right) K_1\left(\frac{m_T \cosh(\rho)}{T}\right)$$

where $$\rho = \tanh^{-1}\left(\beta_{boost}\right)$$

- **Simple assumption: uniform sphere of radius R and boost velocity varies linearly w/ r:**

$$\frac{1}{m_T}\frac{dN}{dm_T} \propto \int_0^R r^2 dr\, m_T I_0\left(\frac{p_T \sinh(\rho)}{T}\right) K_1\left(\frac{m_T \cosh(\rho)}{T}\right)$$

$$\rho(r) = \tanh^{-1}\left(\beta_T^{MAX} \frac{r}{R}\right)$$

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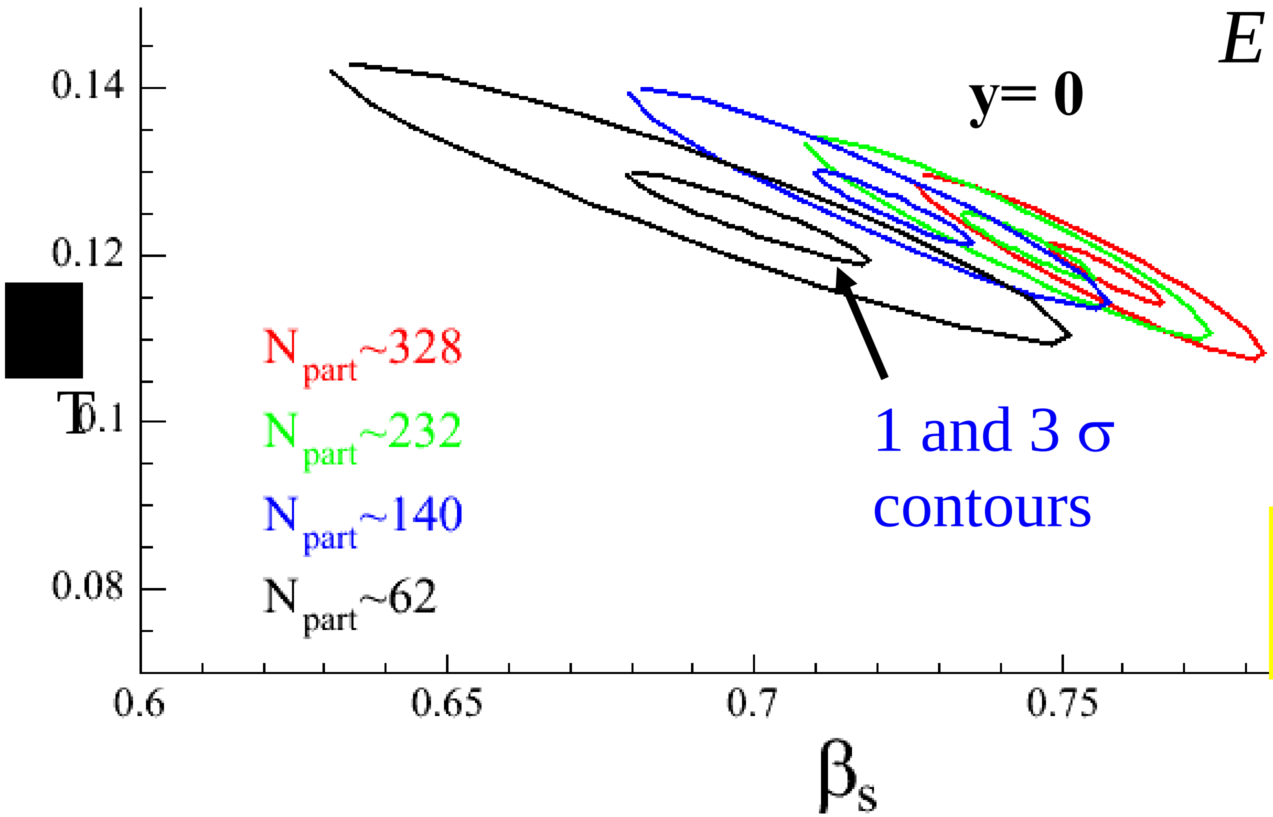
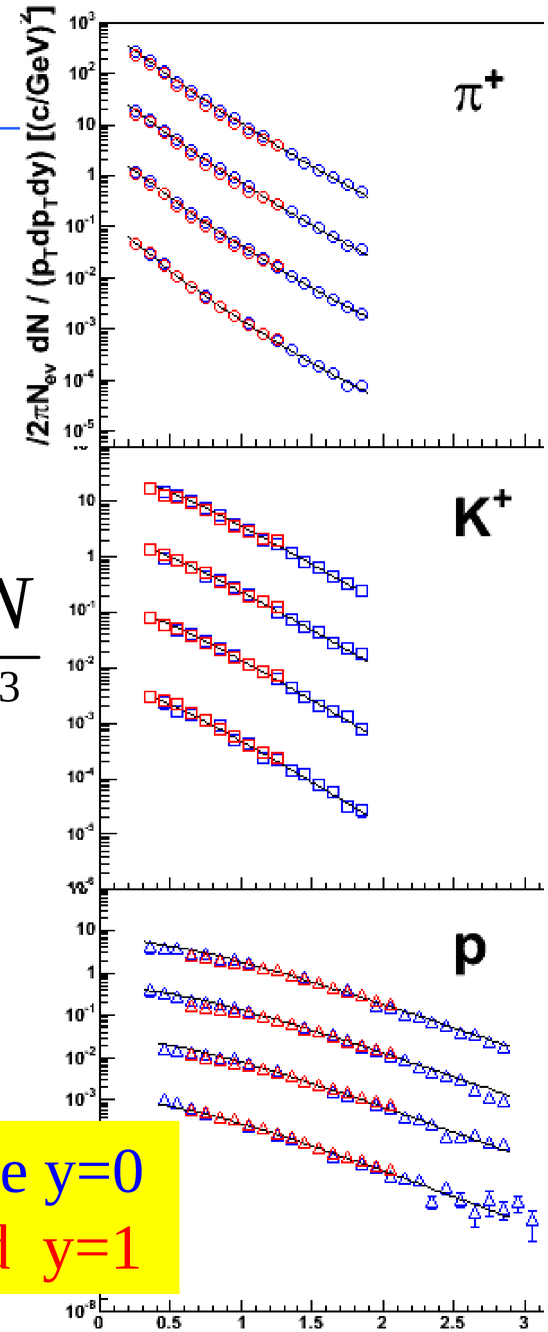
Blast Wave Fits

Fit AuAu spectra to blast wave model:
- **β_S (surface velocity) drops with $dN/d\eta$**
- **T (temperature) almost constant.**



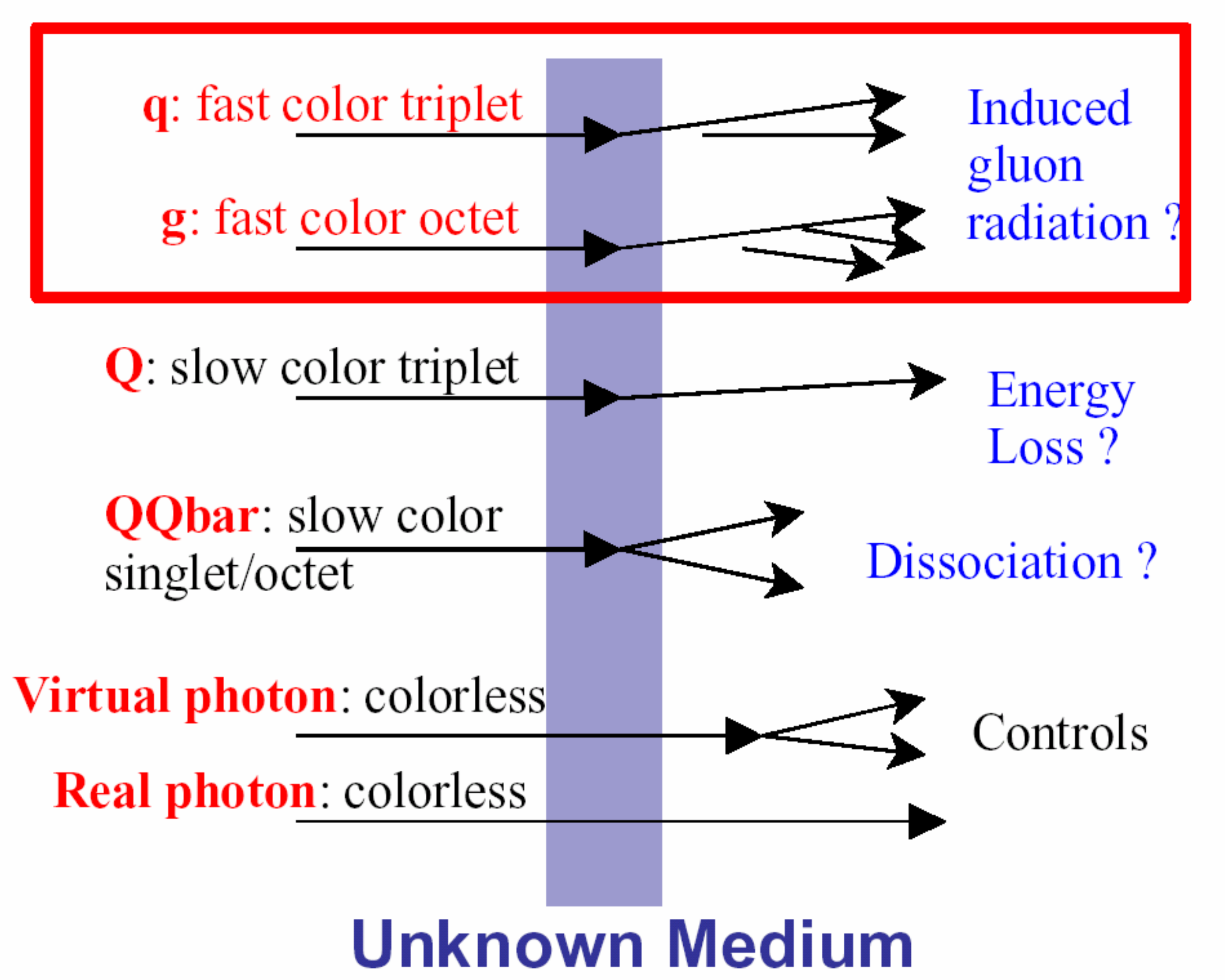
$$E\frac{d^3N}{dp^3}$$



Is There a There There?

- We accelerate nuclei to high energies with the hope and intent of utilizing the beam energy to drive a phase transition to QGP.
- The collision must not only utilize the energy effectively, but generate the signatures of the new phase for us.
- I will make an artificial distinction as follows:
  - Medium: The bulk of the particles; dominantly soft production and possibly exhibiting some phase.
  - Probe: Particles whose production is calculable, measurable, and thermally incompatible with (distinct from) the medium.
- The medium & probe paradigm will establish whether there is a there there.

The Probes Gallery:



Jet Suppression

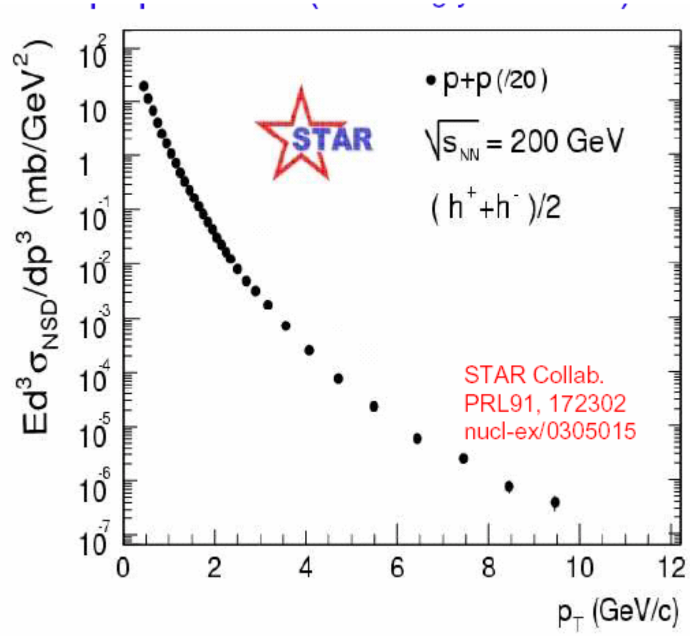
charm/bottom dynamics

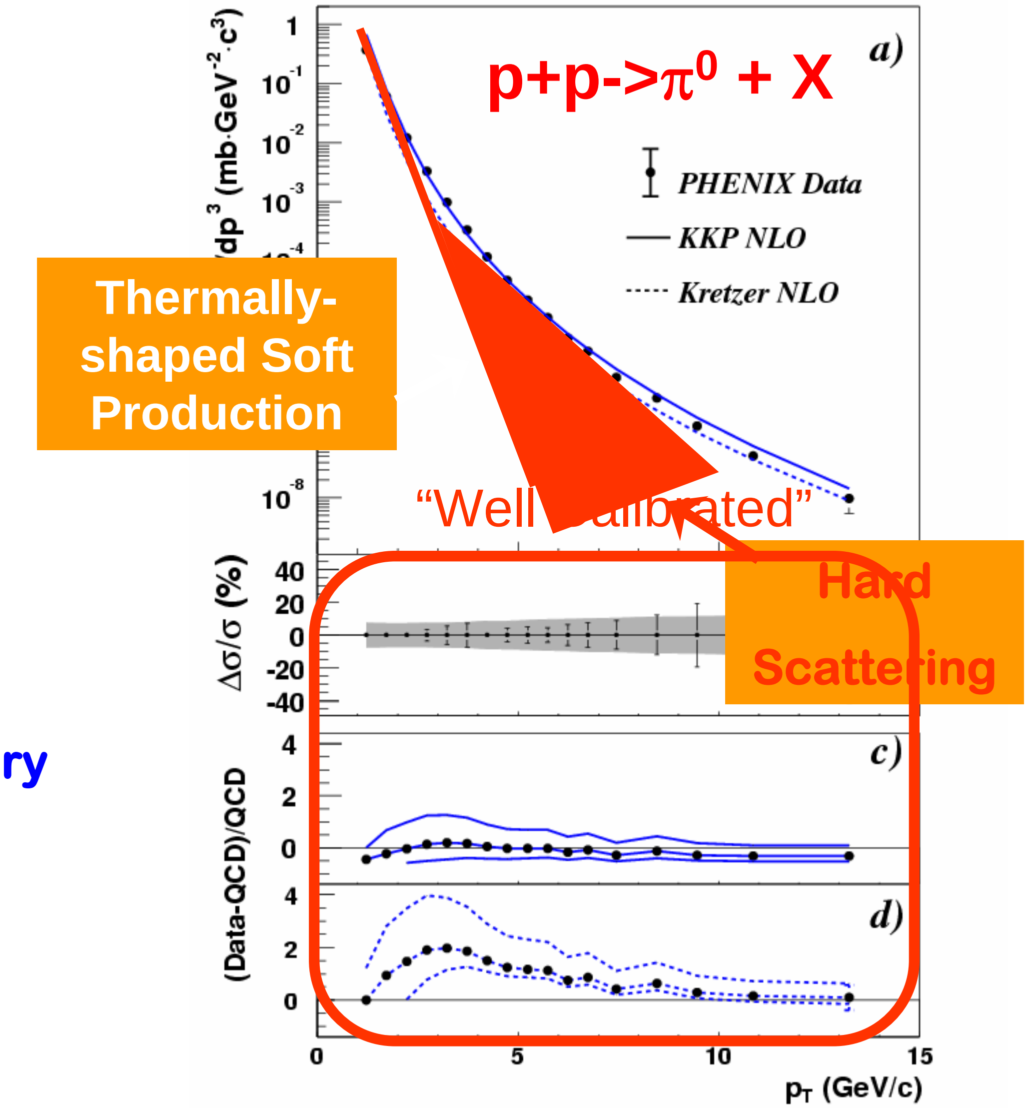
J/Ψ & Υ

direct photons
CONTROL

The importance of the control measurement(s) cannot be overstated!

Calibrating the Probe(s)





- **Measurement from elementary collisions.**
- **"The tail that wags the dog" (M. Gyulassy)**

hep-ex/0305013 S.S. Adler et al.

R_{AA} Normalization

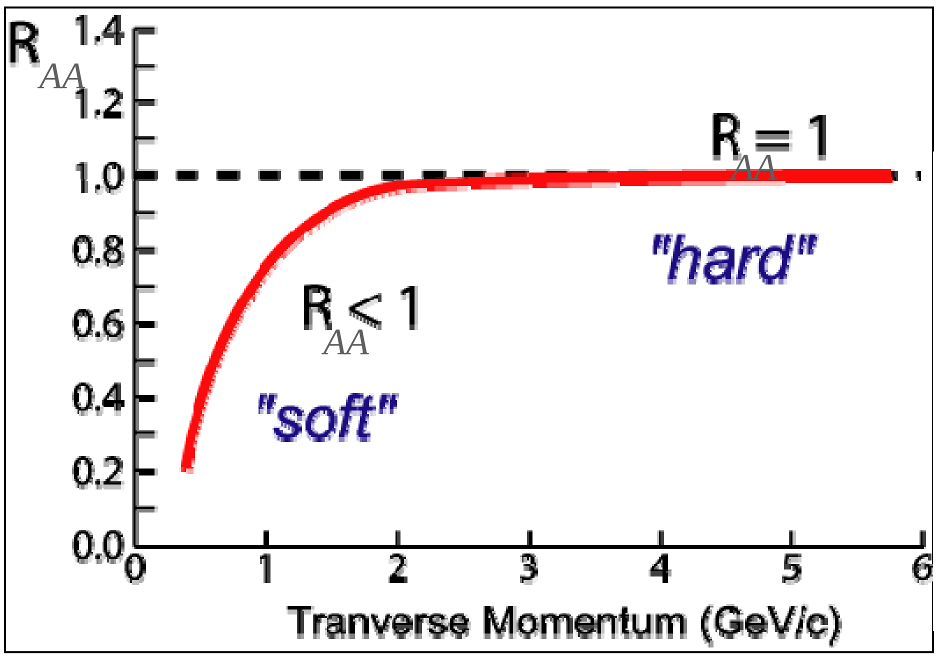
1. Compare Au+Au to nucleon-nucleon cross sections
2. Compare Au+Au central/peripheral

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

nucleon-nucleon cross section

$\langle N_{binary} \rangle / \sigma_{inel}^{p+p}$



If no "effects":
- $R_{AA} < 1$ in regime of soft physics
- $R_{AA} = 1$ at high-p_T where hard scattering dominates

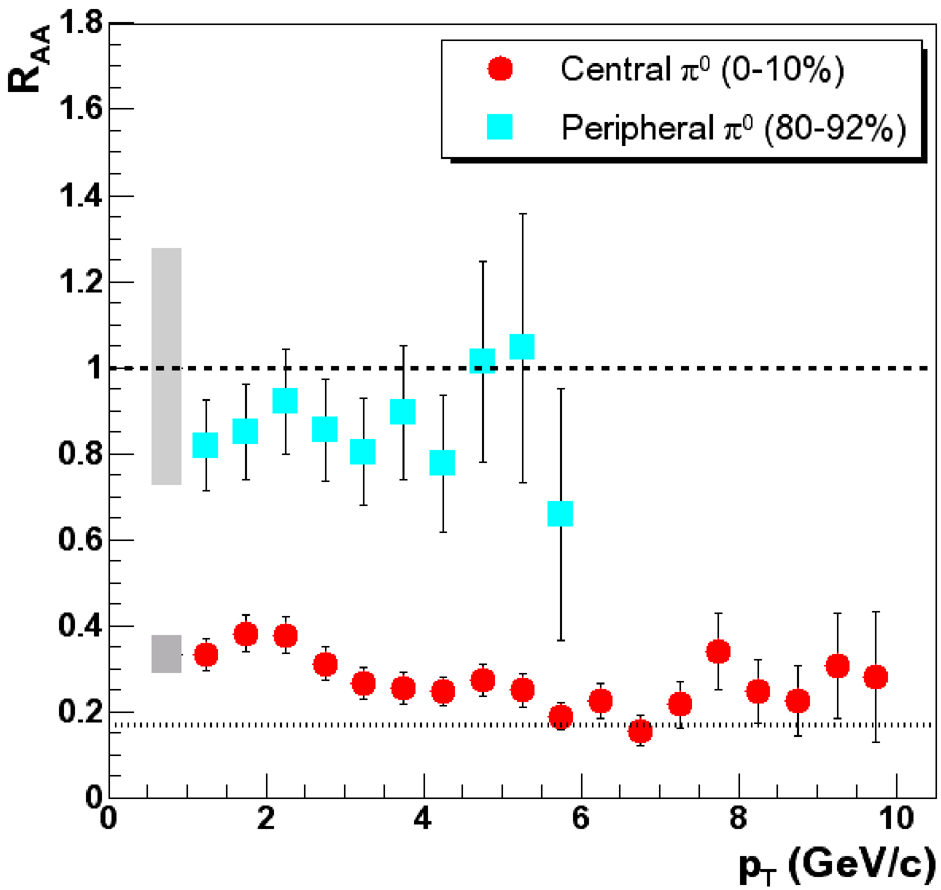
Suppression:
- $R_{AA} < 1$ at high-p_T

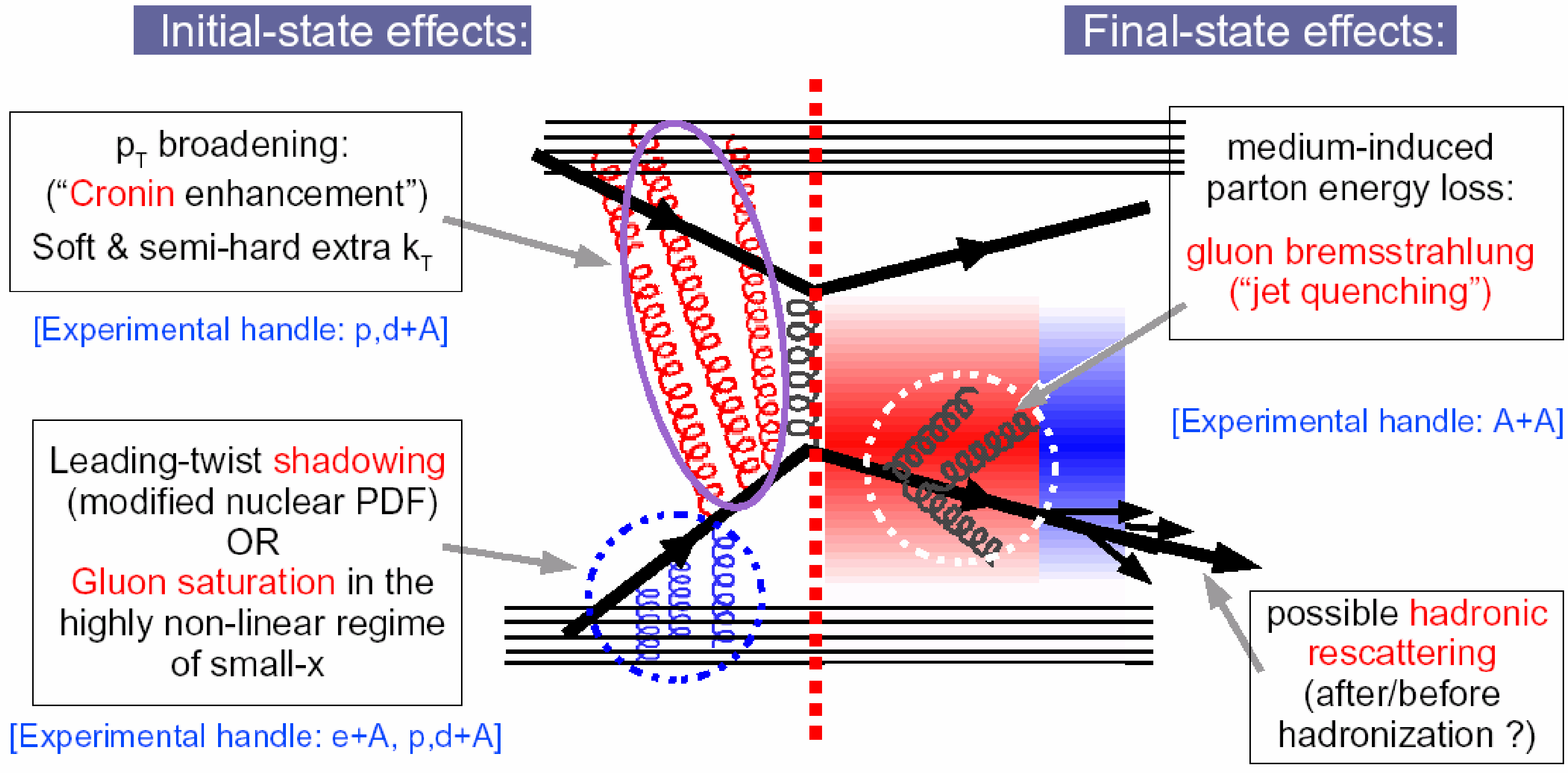
Au-Au $\sqrt{s}$ = 200 GeV: high p_T suppression!

PRL91, 072301(2003)

PHENIX

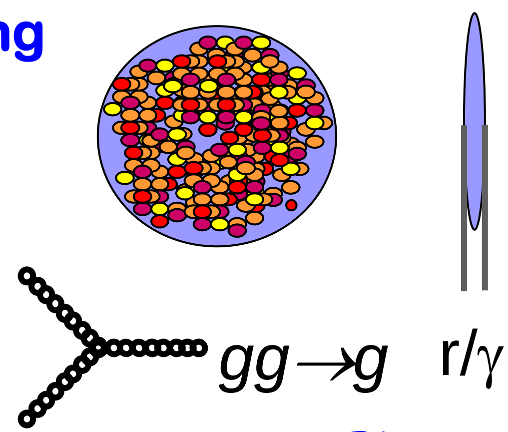
$$R_{AA} = \frac{\text{Yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\text{Yield}_{pp}}$$



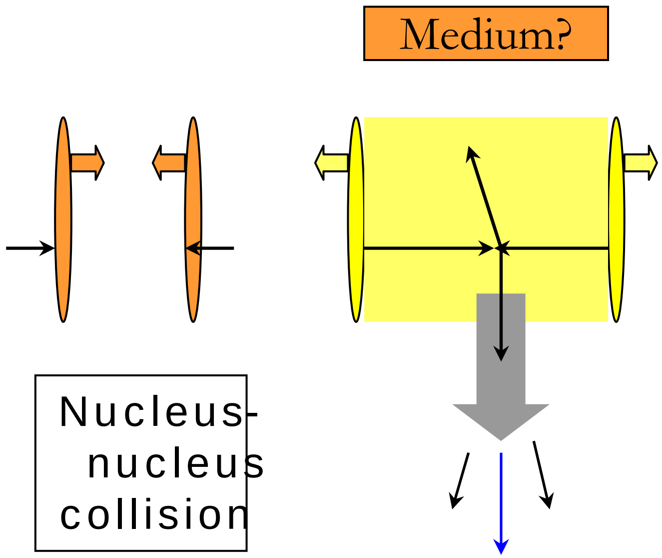


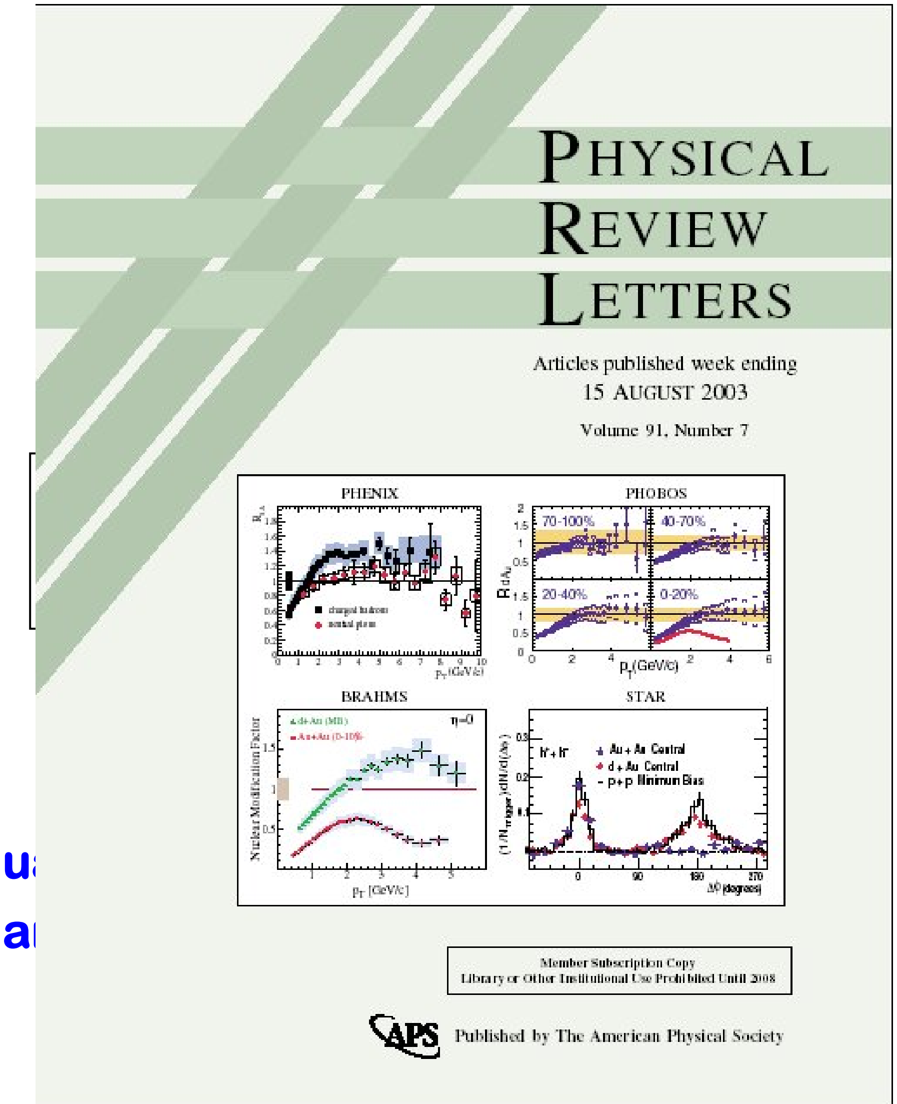
- **Color Glass Condensate**
- **Gluon fusion reduces number of scattering centers in initial state.**
- **Theoretically attractive; limits DGLAP evolution/restores unitarity**

probe rest frame



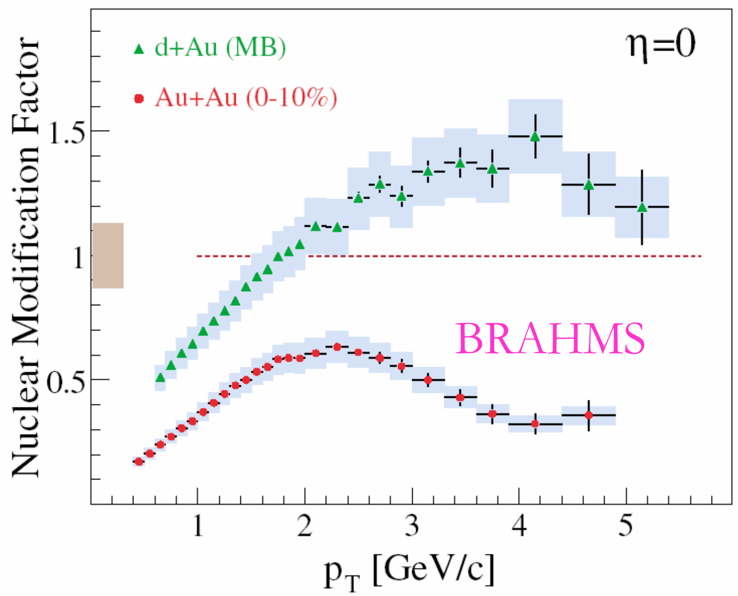
Control Experiment

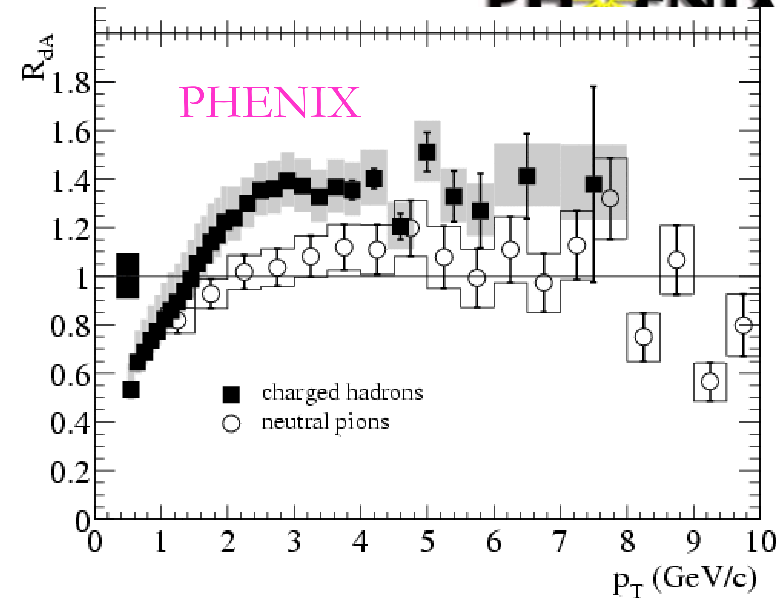


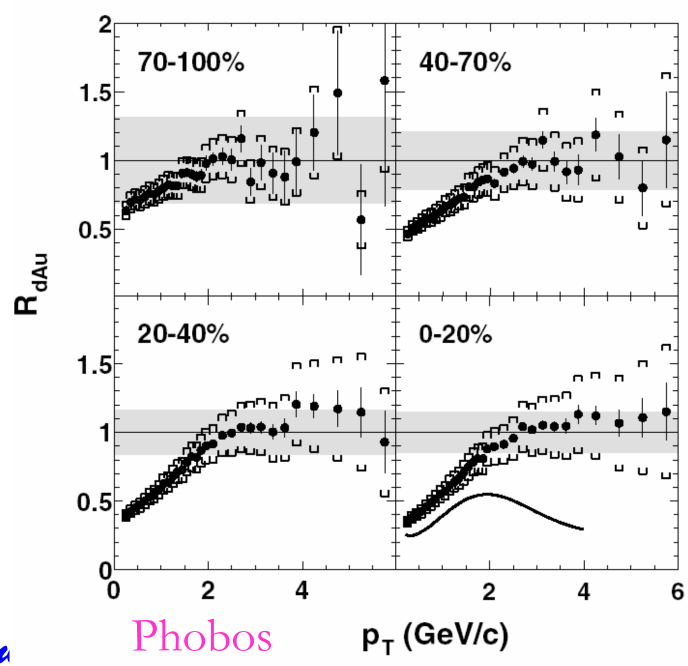


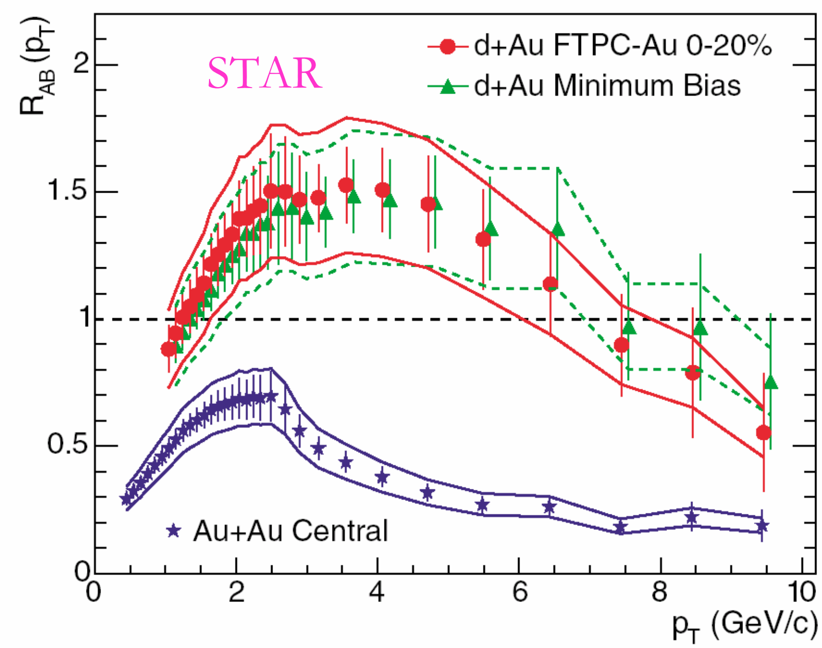
- **Collisions of small with large nuclei qu**
- **Small + Large distinguishes all initial a**

NO suppression in d+Au!

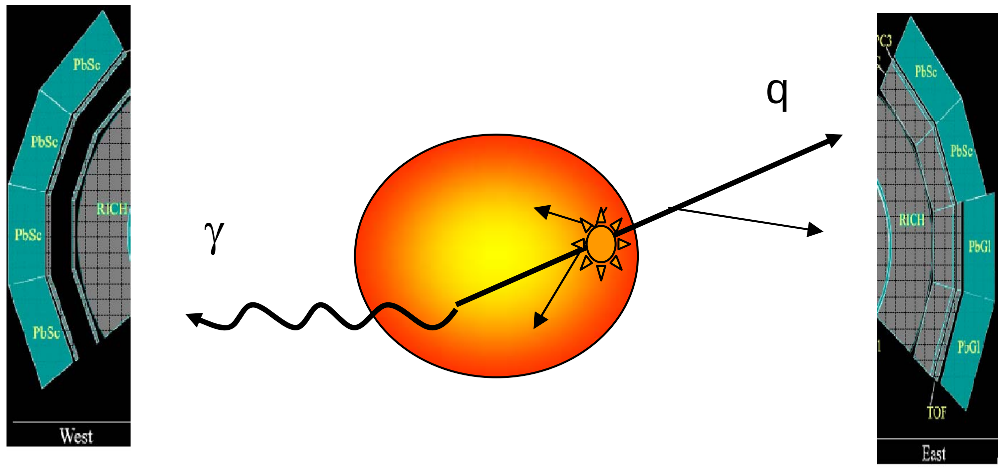






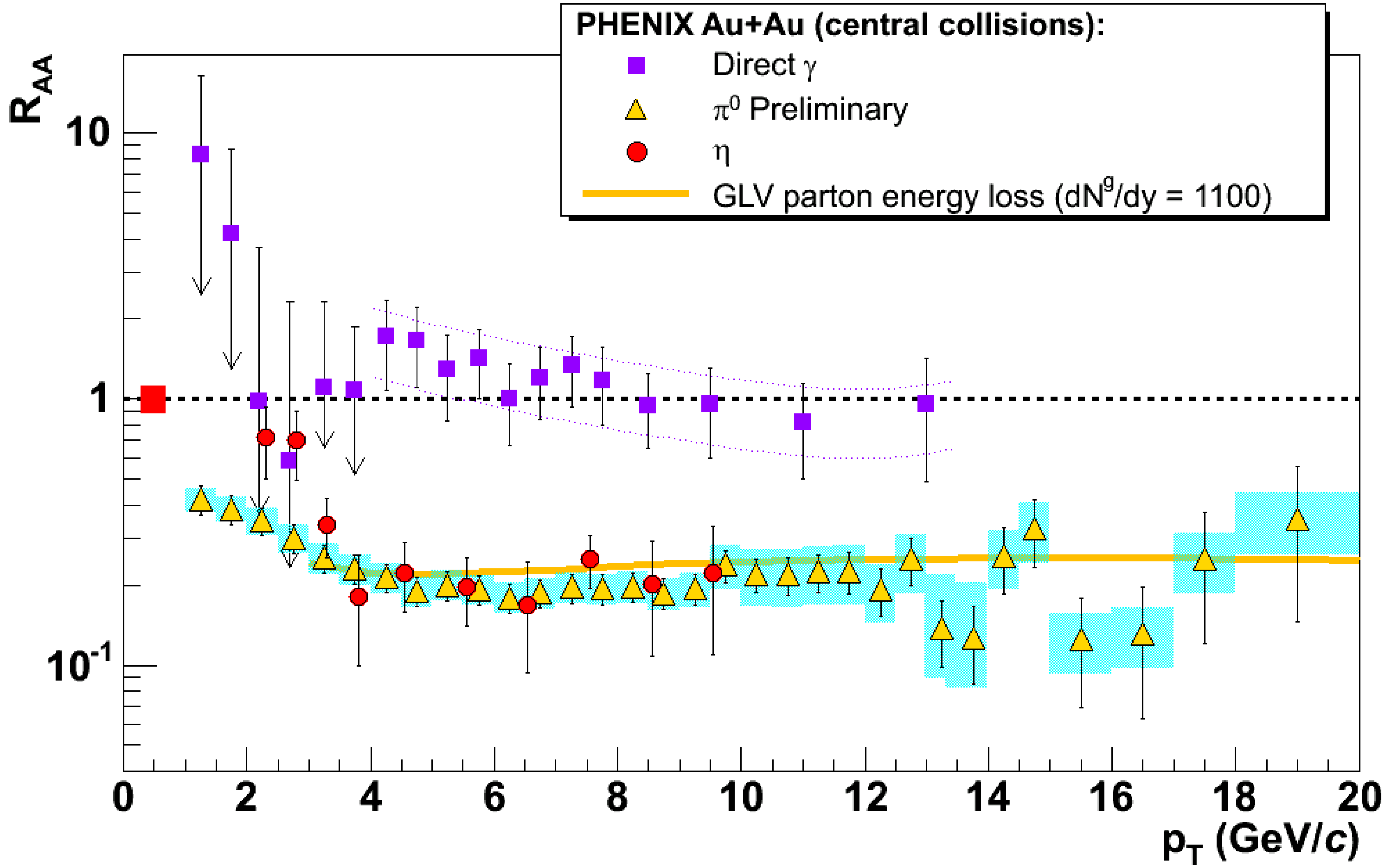


Experiment



- The medium should be transparent to photons.
- These thereby probe the initial rate of pQCD production and provide independent normalization of hard collision rates.

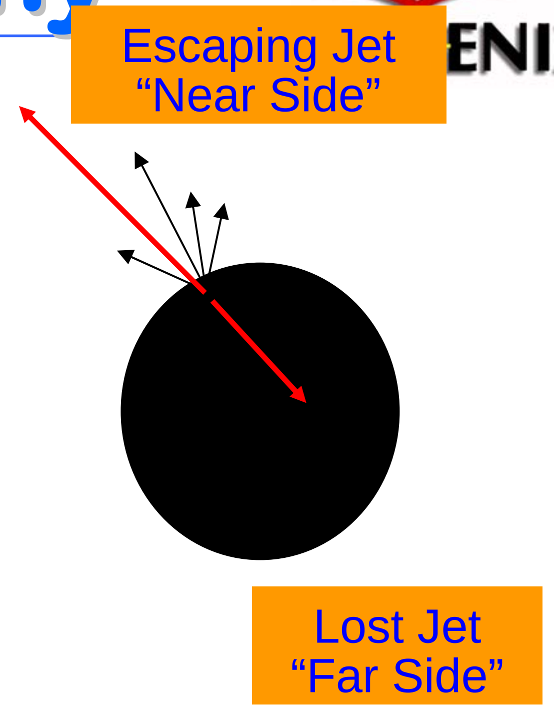
pQCD Photons!

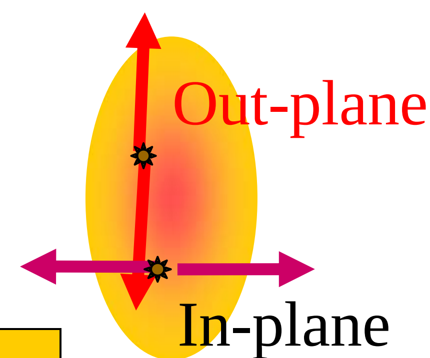


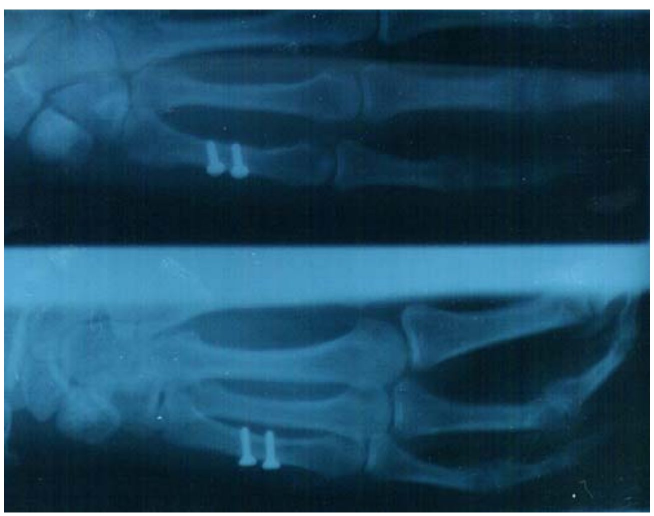
- Data consistent with hard scattering at pQCD rates plus suppression.
- Jet Quenching again proves to be a final state effect!

Jet Tomography

- **Tomography, a fancy word for a shadow!**
- **Jets are produced as back-to-back pairs.**
- **One jet escapes, the other is shadowed.**
- **Expectation:**
  - **“Opaque” in head-on collisions.**
  - **“Translucent” in partial overlap collisions.**







X-ray pictures are shadows of bones

Can Jet Absorption be Used to “Take an X-ray” of our Medium?

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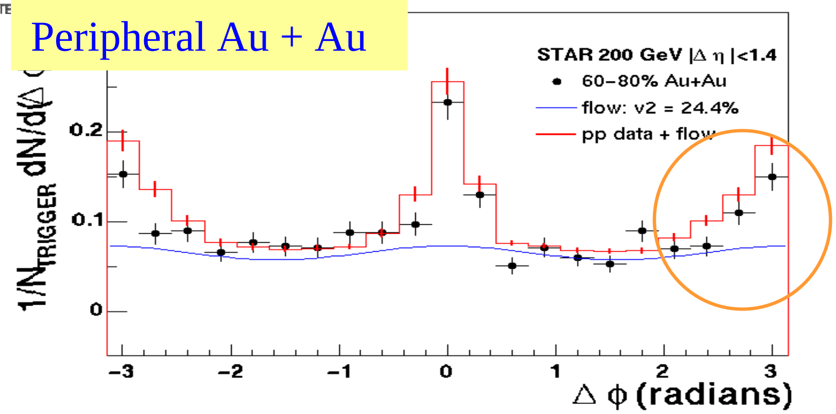
Back-to-back jets

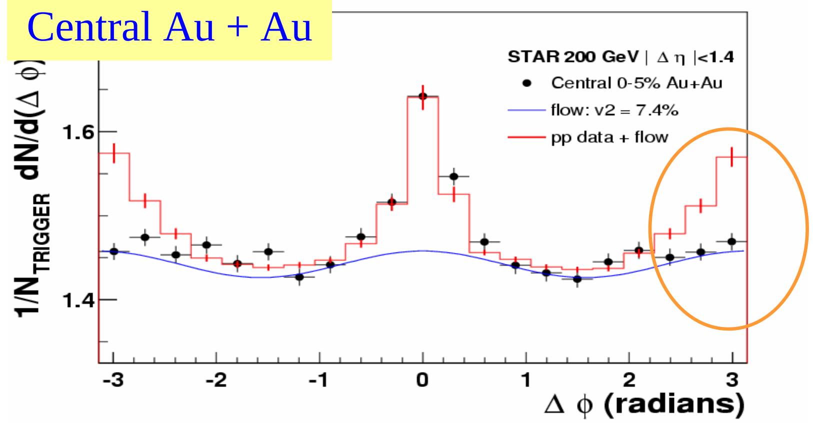
STAR PRL 90, 082302 (2003)

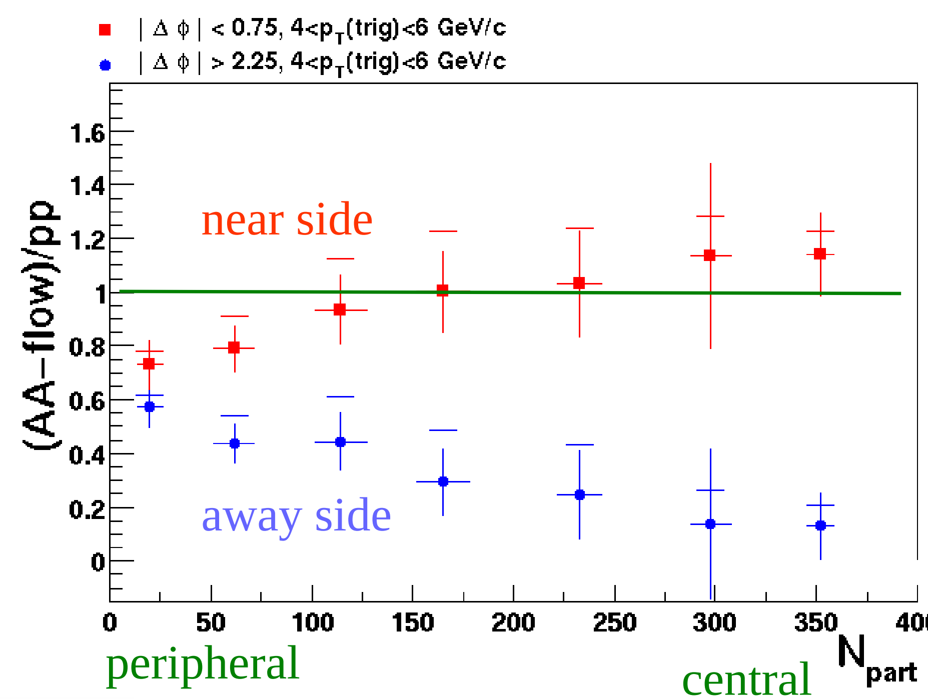
$$D_2(Au+Au) = D_2(p+p) + B(1+v_2^2\cos(2\Delta\phi))$$

Peripheral Au + Au

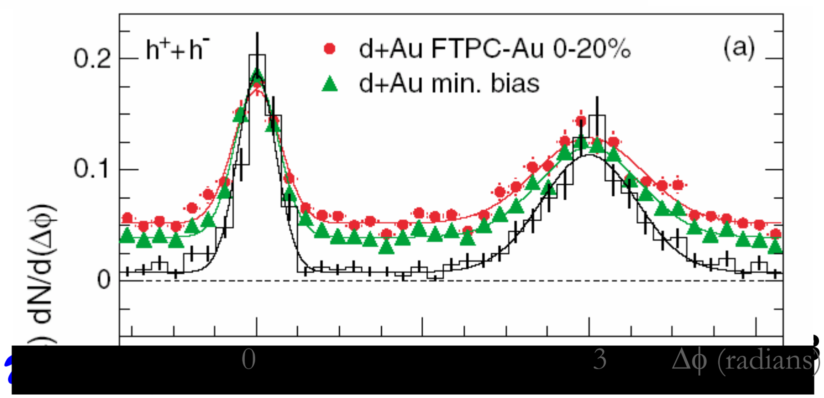


Central Au + Au



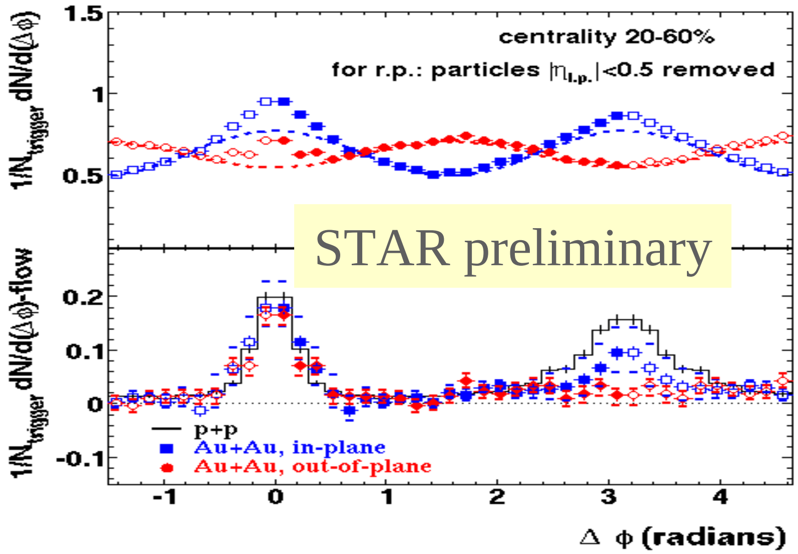


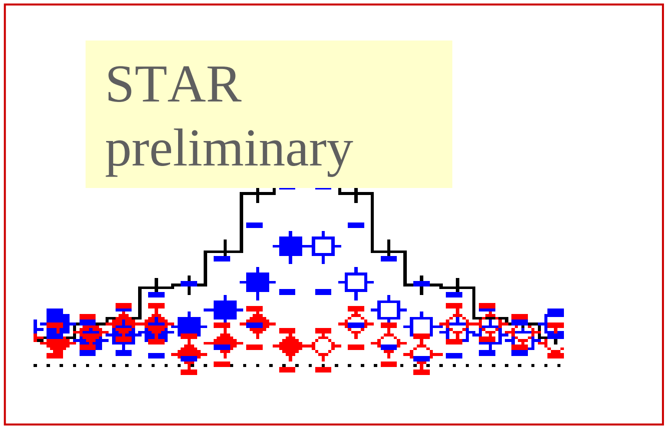
d + Au control

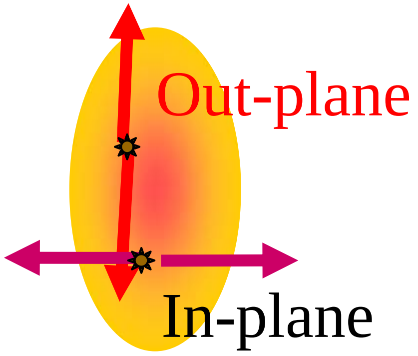


- **Away-side sensitive to precise v_2 value.**
- **Desire precision technique to disentangle v_2.**

Back-to-Back wrt Reaction Plane





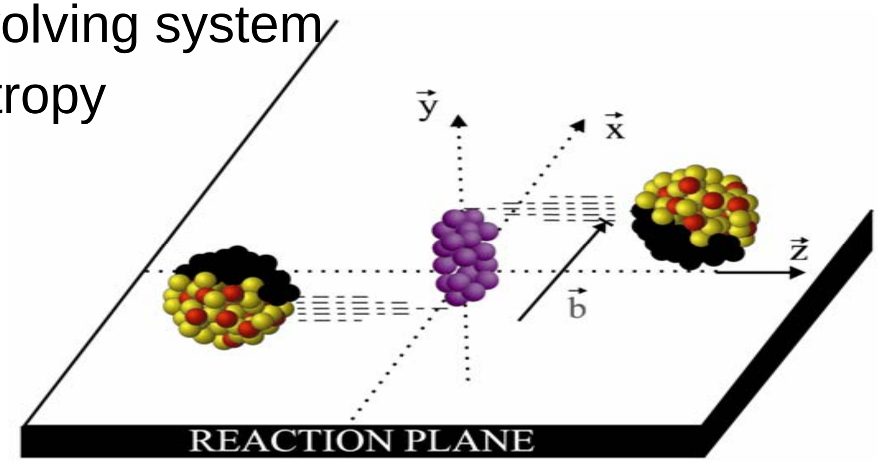


- **Suppression stronger in the out-of-plane direction.**
- **Indicates suppression depends upon length of medium traversed.**

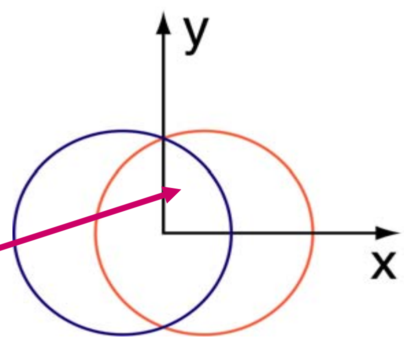
“elliptic flow” barometer

Origin: spatial anisotropy of the system when created, followed by multiple scattering of particles in the evolving system

spatial anisotropy $\rightarrow$ momentum anisotropy

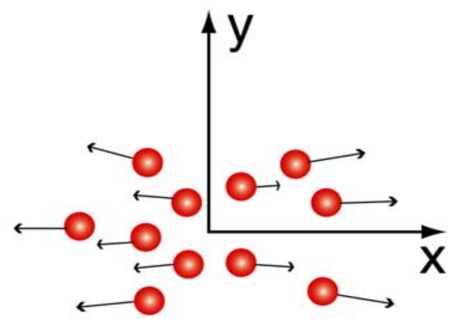


v_2: 2nd harmonic *Fourier coefficient* in azimuthal distribution of particles with respect to the reaction plane



Almond shape overlap region in coordinate space

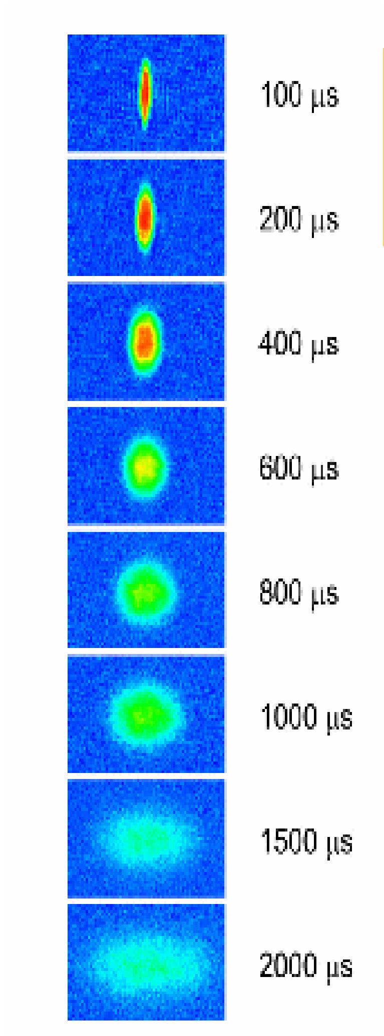
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$



$$v_2 = \langle \cos 2\phi \rangle \qquad \phi = \operatorname{atan}\frac{p_y}{p_x}$$

Anisotropic Flow

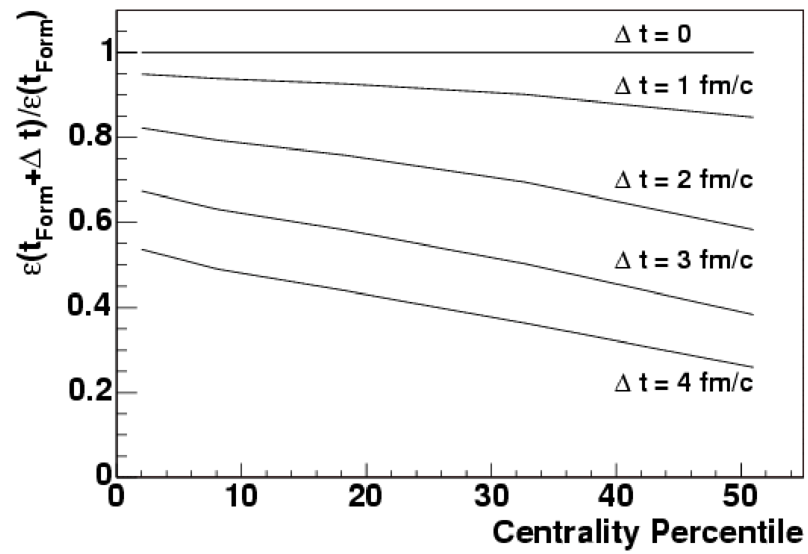
Liquid Li Explodes into Vacuum



Position Space anisotropy (eccentricity) is transferred to a momentum space anisotropy visible to experiment

- Gases explode into vacuum uniformly in all directions.
- Liquids flow violently along the short axis and gently along the long axis.
- We can observe the RHIC medium and decide if it is more liquid-like or gas-like

- Process is SELF-LIMITING
- Sensitive to the initial time



- Delays in the initiation of anisotropic flow not only change the magnitude of the flow but also the centrality dependence increasing the sensitivity of the results to the initial time.

Fourier Expansion

- Most general expression for ANY invariant cross section uses explicit Fourier-Series for explicit ϕ dependence:

$$\frac{1}{p_T}\frac{d^3N}{dp_T d\phi dy} = \frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy}\left[1 + 2v_1(p_T, y)\cos(\phi) + 2v_2(p_T, y)\cos(2\phi) + \ldots\right]$$

here the sin terms are skipped by symmetry agruments.

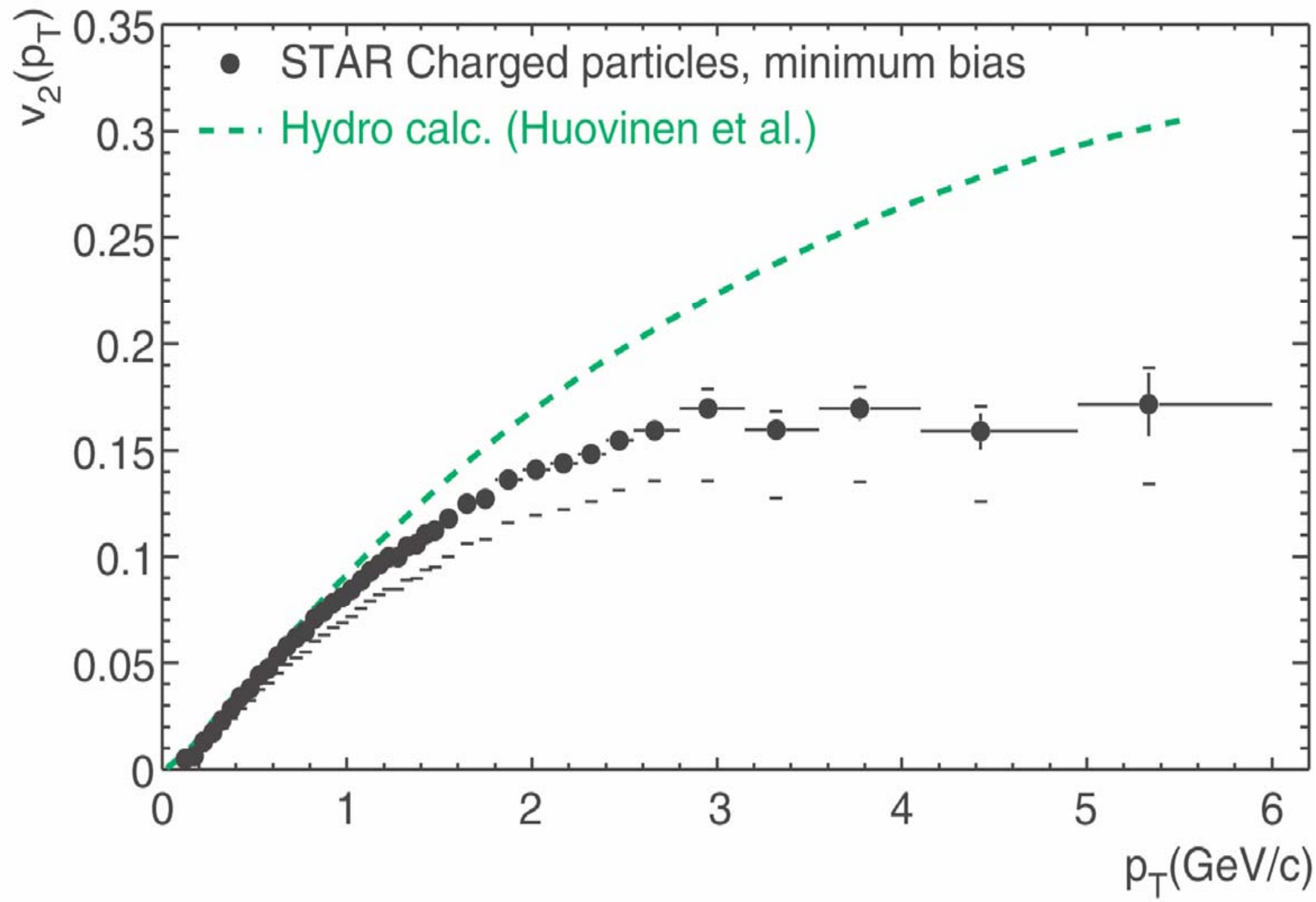
- For a symmetric system (AuAu, CuCu) at y=0, v_{odd} vanishes

$$\frac{1}{p_T}\frac{d^3N}{dp_T d\phi dy} = \frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy}\left[1 + 2v_2(p_T)\cos(2\phi) + 2v_4(p_T)\cos(4\phi) + \ldots\right]$$

- v_4 and higher terms are non-zero and measured but will be neglected for this discussion.

$$\frac{1}{p_T}\frac{d^3N}{dp_T d\phi dy} = \frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy}\left[1 + 2v_2(p_T)\cos(2\phi)\right]$$

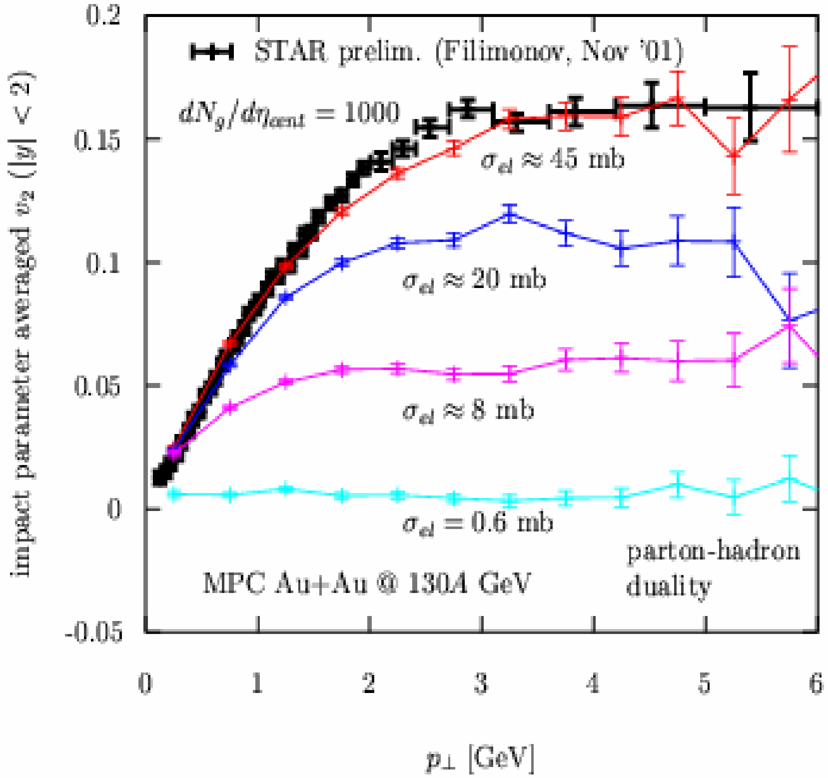
Just how big is v_2?



Yup, that's pretty big

Adler et al., nucl-ex/0206006

Parton Cascade Calculation of v_2



parton transport solutions via MPC 1.6.0 [D.M. & Gyulassy, NPA 697 ('02)]

$$p^\mu \partial_\mu f_i = S_i + C_i^{2\to 2}[f] + \ldots$$

minijet initial conditions

$1g \longrightarrow 1\pi$ hadronization

Huge cross sections!!

- **saturation pattern can be reproduced with elastic $2 \to 2$ interactions,**

requires large opacities $\sigma_{el} \times dN_g/d\eta \approx 45000$ mb $\gg$ pQCD (3 mb $\times 1000$)

- large opacities also suggested by pion HBT data [D.M & Gyulassy, nucl-th/0211017]


Splash!

Basics of Hydrodynamics

Hydrodynamic Equations

$$\partial_\mu T^{\mu\nu} = 0,$$ Energy-momentum conservation

$$\partial_\mu n_i^\mu = 0$$ Charge conservations (baryon, strangeness, etc…)

For perfect fluids (neglecting viscosity),

$$T^{\mu\nu} = (\boxed{e} + \boxed{P})u^\mu \boxed{u^\nu} - P g^{\mu\nu}$$

Energy density | Pressure | 4-velocity

Need equation of state (EoS)

$P(e,n_B)$

to close the system of eqs.
→ Hydro can be connected directly with lattice QCD

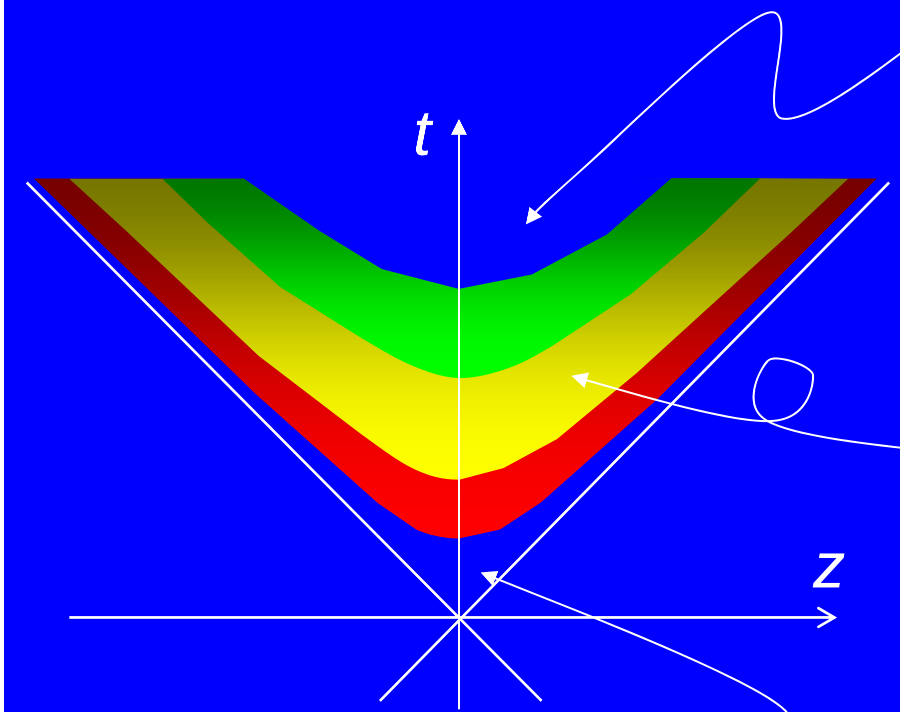
Within ideal hydrodynamics, pressure gradient *dP*/*dx* is the driving force of collective flow.

→ Collective flow is believed to reflect information about EoS!

→ Phenomenon which connects 1st principle with experiment

Caveat: Thermalization, $\lambda \ll$ (typical system size)

Inputs to Hydrodynamics



Final stage:
Free streaming particles
→ Need decoupling prescription

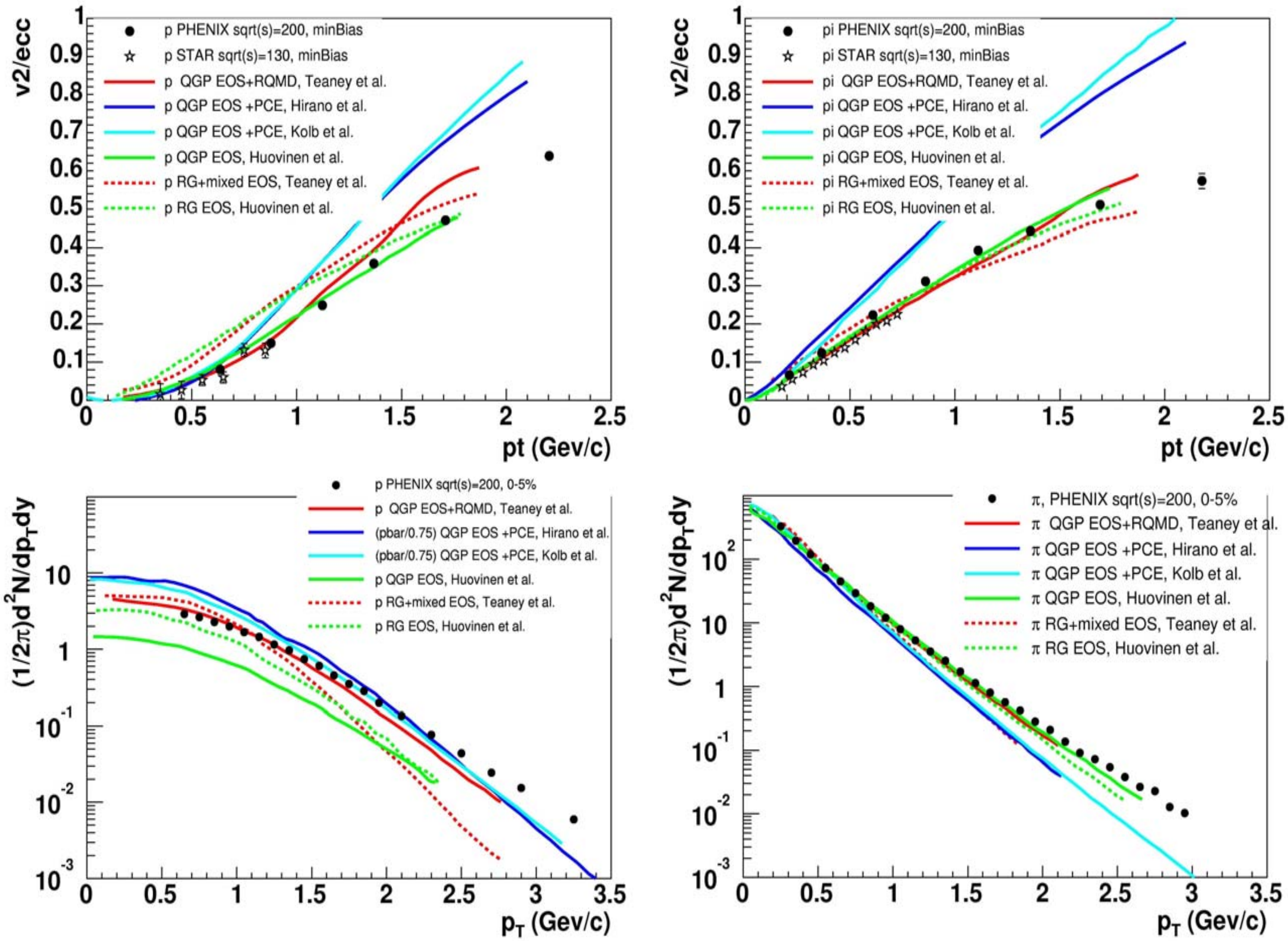
Intermediate stage:
Hydrodynamics can be valid if thermalization is achieved.
→ Need EoS

Initial stage:
Particle production and pre-thermalization beyond hydrodynamics
→Instead, initial conditions for hydro simulations

Need modeling
(1) EoS, (2) Initial cond., and (3) Decoupling

v_2 AND- spectra

proton pion **nucl-ex/0410003**



Hydro models:

Teaney
(w/ & w/o RQMD)

Hirano
(3d)

Kolb

Huovinen
(w/& w/o QGP)

Hydro-models Score Board

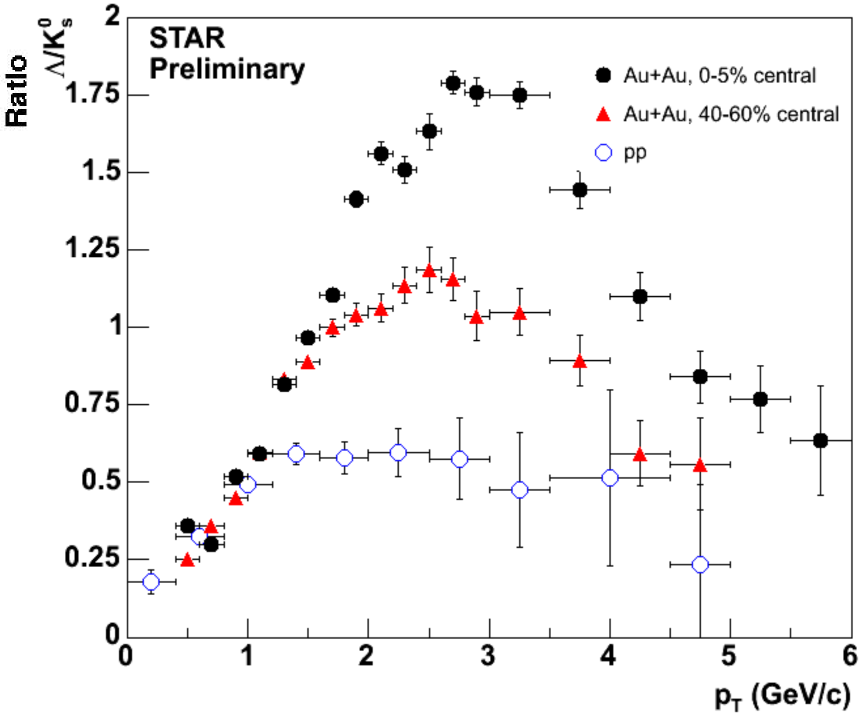
	QGP+mixed+RG				mixed+RG	RG
	Teaney	Hirano	Kolb	Huovinen	Teaney	Huovinen
latent heat (GeV/fm^3)	0.8	1.7	1.15	1.15	0.8	1.15
init. ϵ_{max} (GeV/fm^3)	16.7		23	23	16.7	23
init. $< \epsilon >$ (GeV/fm^3)	11.0	13.5			11.0	
τ_0 fm/c	1.0	0.6	0.6	0.6	1.0	0.6
hadronic stage	RQMD	partial chemical equil.	partial chemical equil.	full equil.	RQMD	full equil.
proton v2	yes	$<$ 0.7 GeV/c	$<$ 0.7 GeV/c	yes	no	no
pion v2	yes	no	no	yes	yes	yes
proton spectra	yes	overpredict	overpredict	no	no	no
pion spectra	yes	$<$ 1 GeV/c	$<$ 1 GeV/c	yes	$<$ 0.7 GeV/c	yes
HBT	Not available	No	Not available	No	Not available	Not available

- **The hydro-models which include both hadronic and QGP phases reproduce the qualitative features of the measured v2(p_T) of pions, kaons, and protons.**
- **These hydro-models require an early thermalization (τ_{therm}<1fm/c) and high initial energy density ε > 10 GeV/fm^3**
- **Several of the hydro-models fail to reproduce the v2 and spectra simultaneously.**
- **HBT source parameters are not reproduced by any hydrodynamic calculations.**

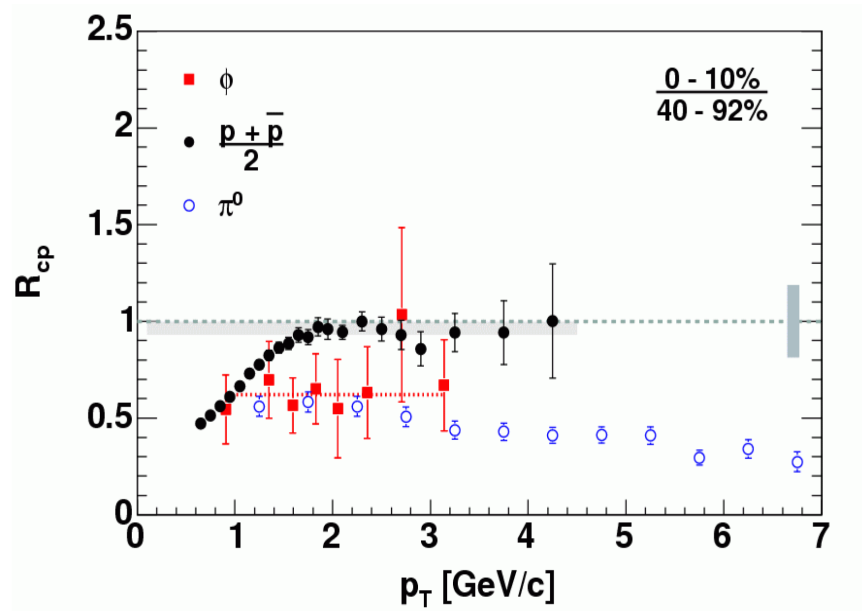
The RHIC data are consistent with the so-called "Hydrodynamic Limit" for a non-viscous relativistic

Anomalous Particle Ratios

Large p/π ratio in 2-4 GeV/c



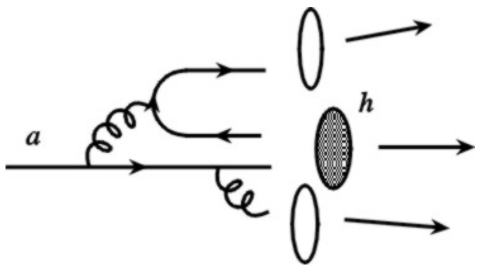
Proton scales with Ncoll
Mesons don't



- Large excesses of baryons are observed at intermediate p_T.
- Why is this not just the flow we discussed yesterday?
  - Flow generates spectral differences based purely on mass.
  - We shall see later that this new effect depends not upon mass but valence quark count.

Recombination Concept

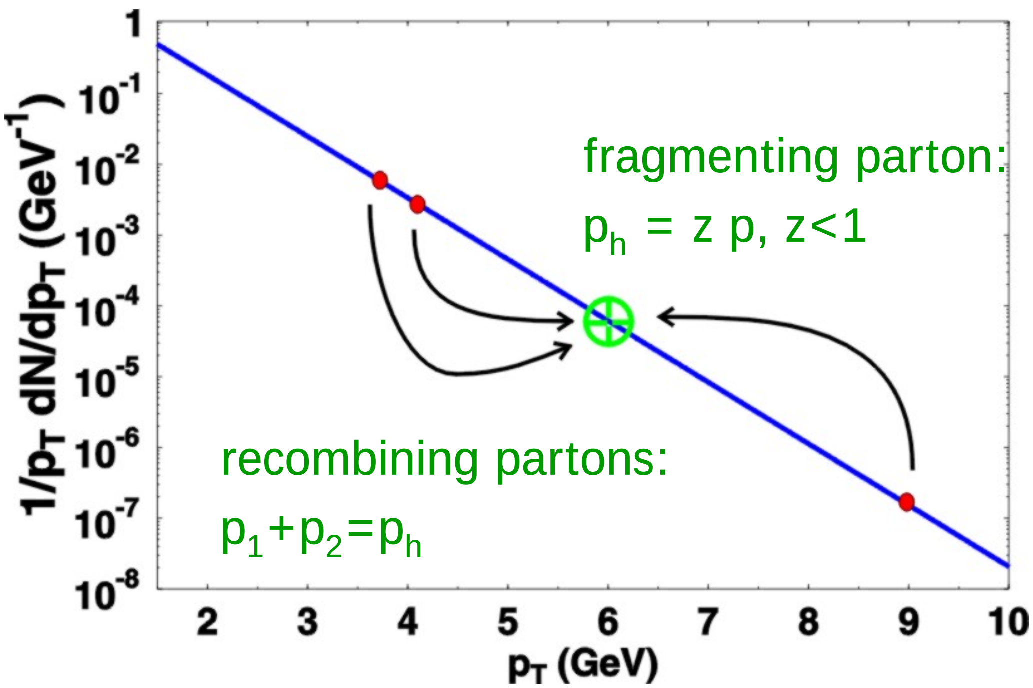
Fragmentation:



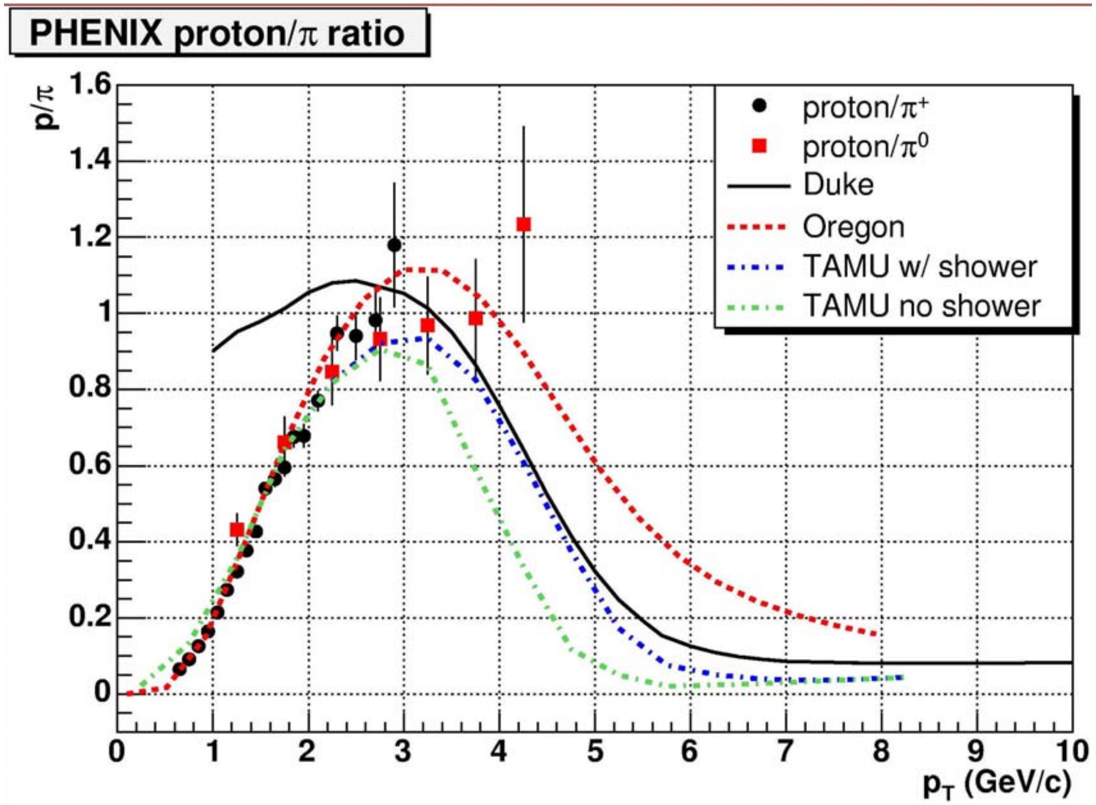
$$E\frac{dN_h}{d^3P} = \int_0^1 \frac{dz}{z^2}\frac{E}{z}\frac{dN_a}{d^3(P/z)}D_{\alpha\to h}(z)$$

- for exponential parton spectrum, recombination is more effective than fragmentation
- baryons are shifted to higher p_t than mesons, for same quark distribution

➢ understand behavior of protons!

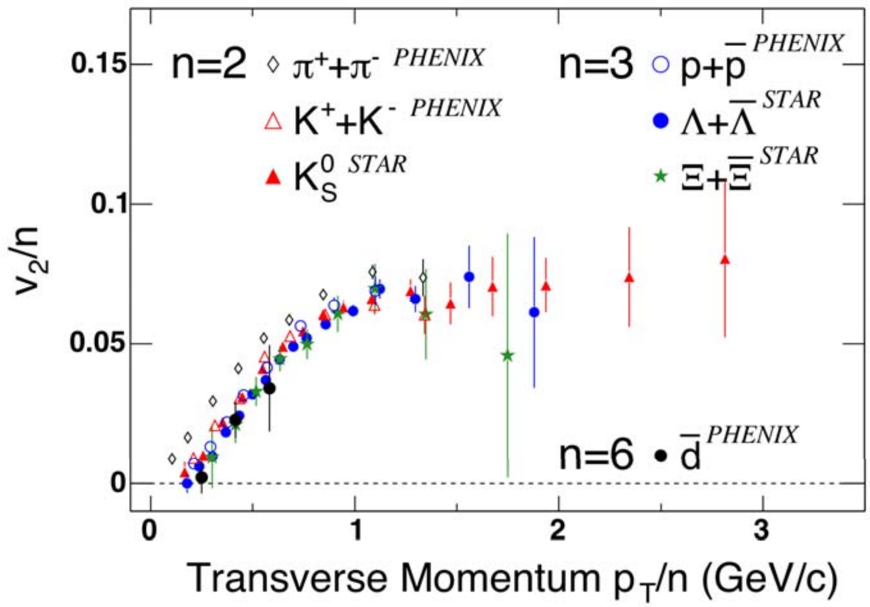


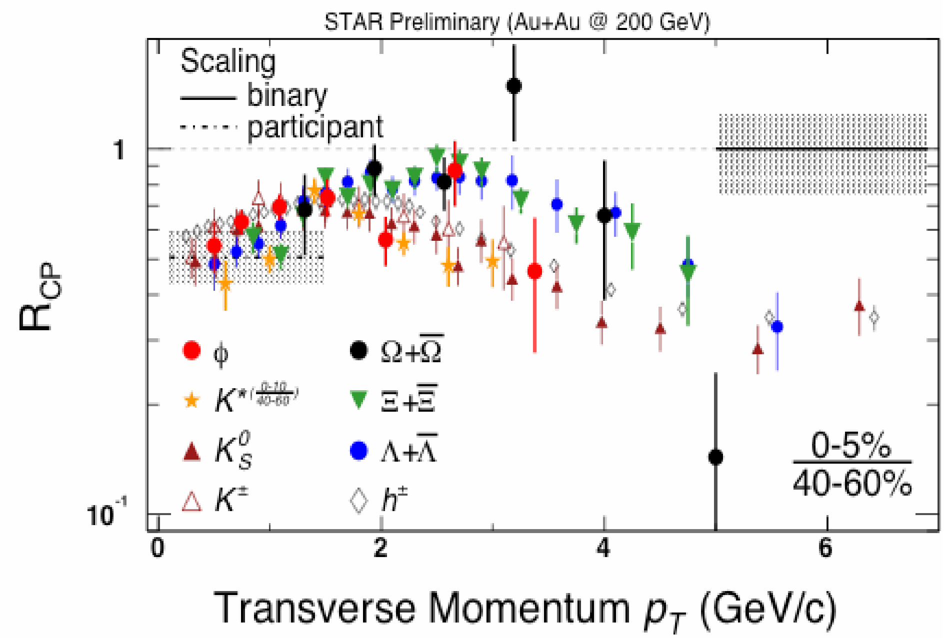
Recombination Models



- **Duke:**
  - Pure thermal reco.
- **Oregon:**
  - Fragmentation itself is recast as a recombination process. HI collision simply adds extra thermal quarks during the process.
- **TAMU:**
  - Jets and also feeddown from resonances.

Recombination Scaling





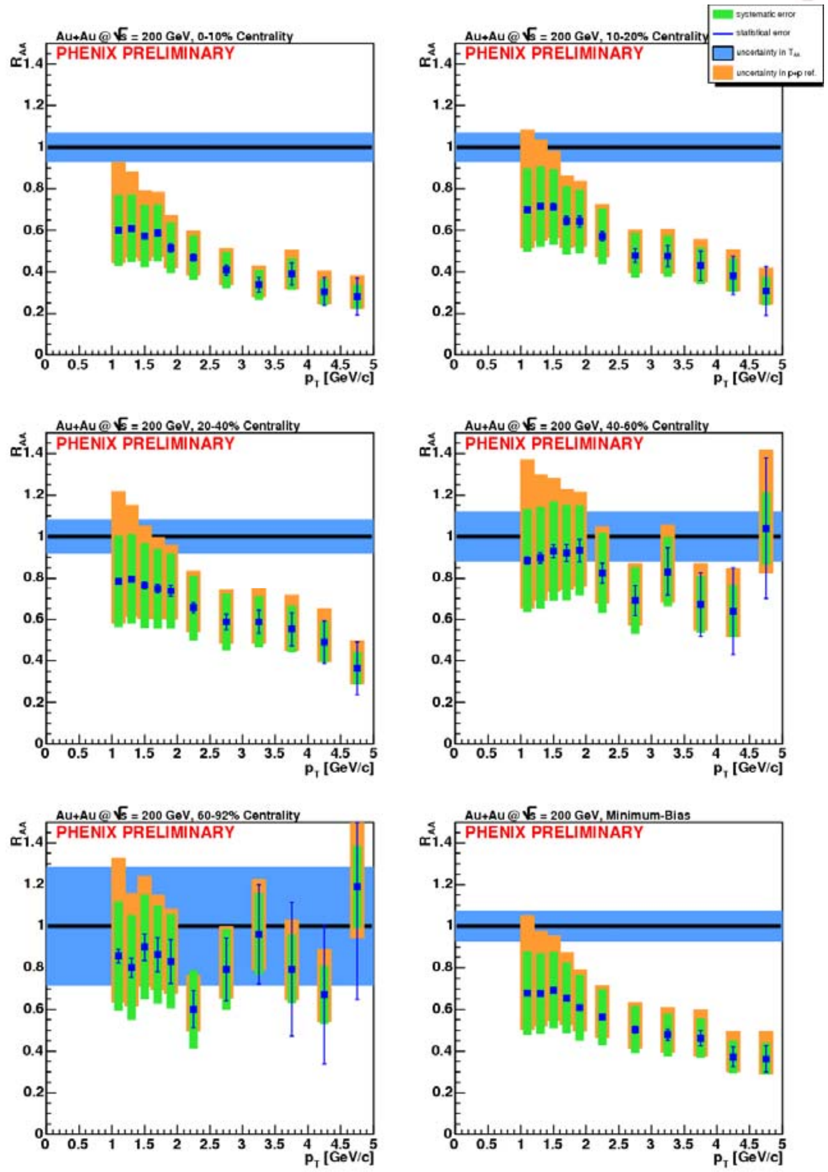
- **The nuclear modification factor when plotted for many particle species shows a bifurcation based upon VALENCE QUARK COUNT (not mass).**
- **The flow patterns for all particles (except pions) are identical when scaled by valence quark count**

HOT#1--R_{AA} of charm electrons

clear evidence for energy loss of charm quarks in central Au + Au!

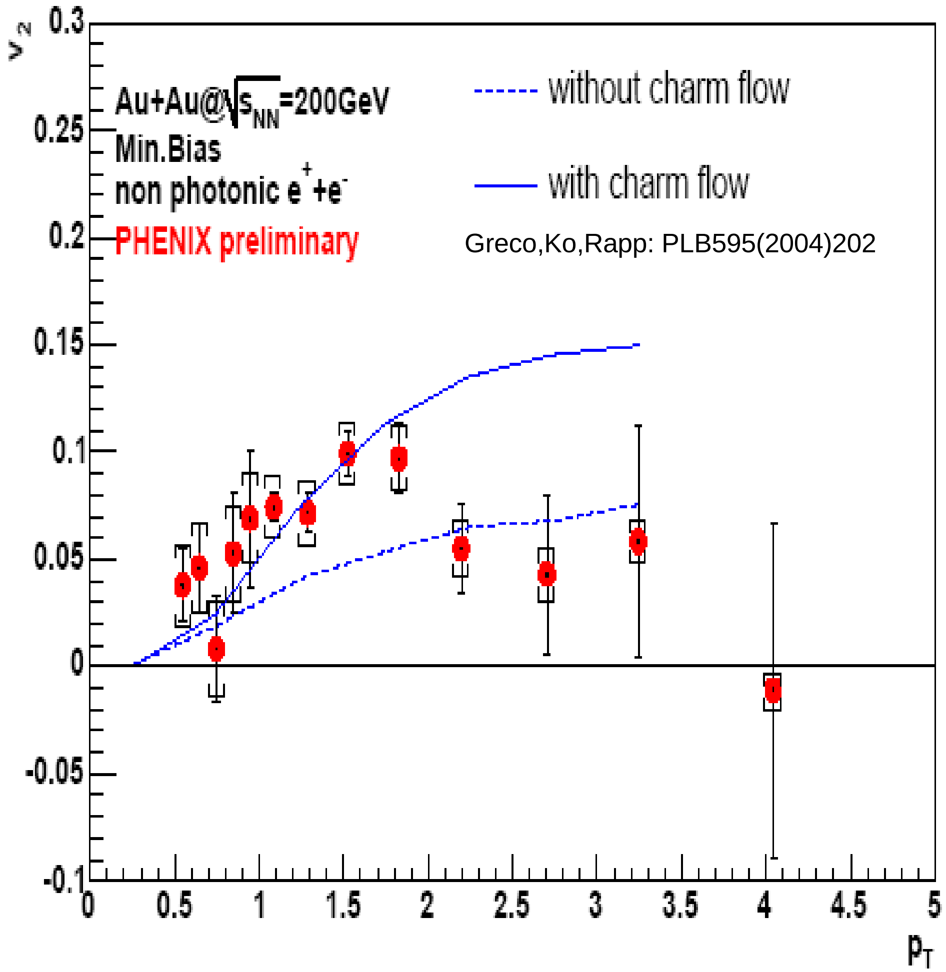
(NOTE: Likely to also be some $e^{\pm}$ from B decays)

R_{AA}



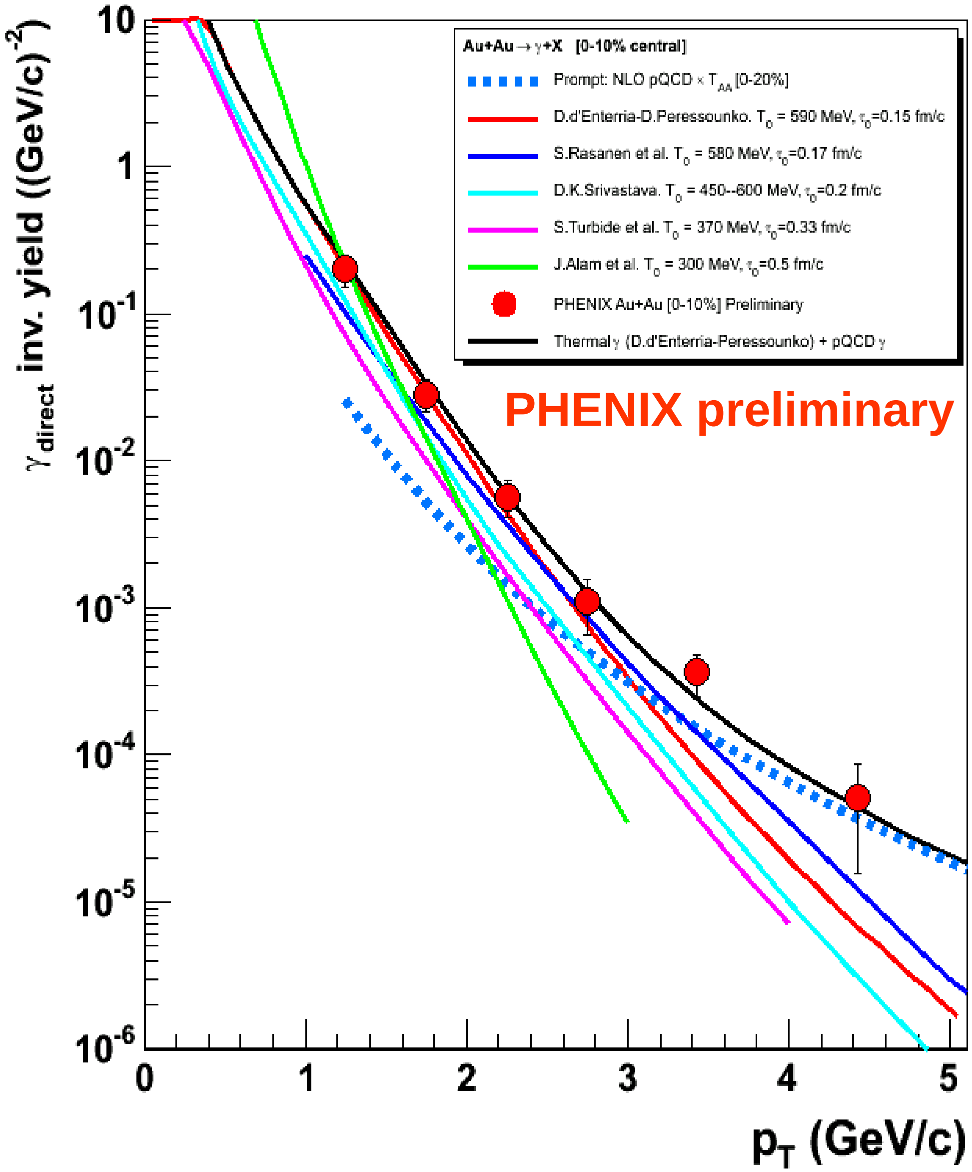
p_T (GeV/c)

Hot#2—Charm Flows!



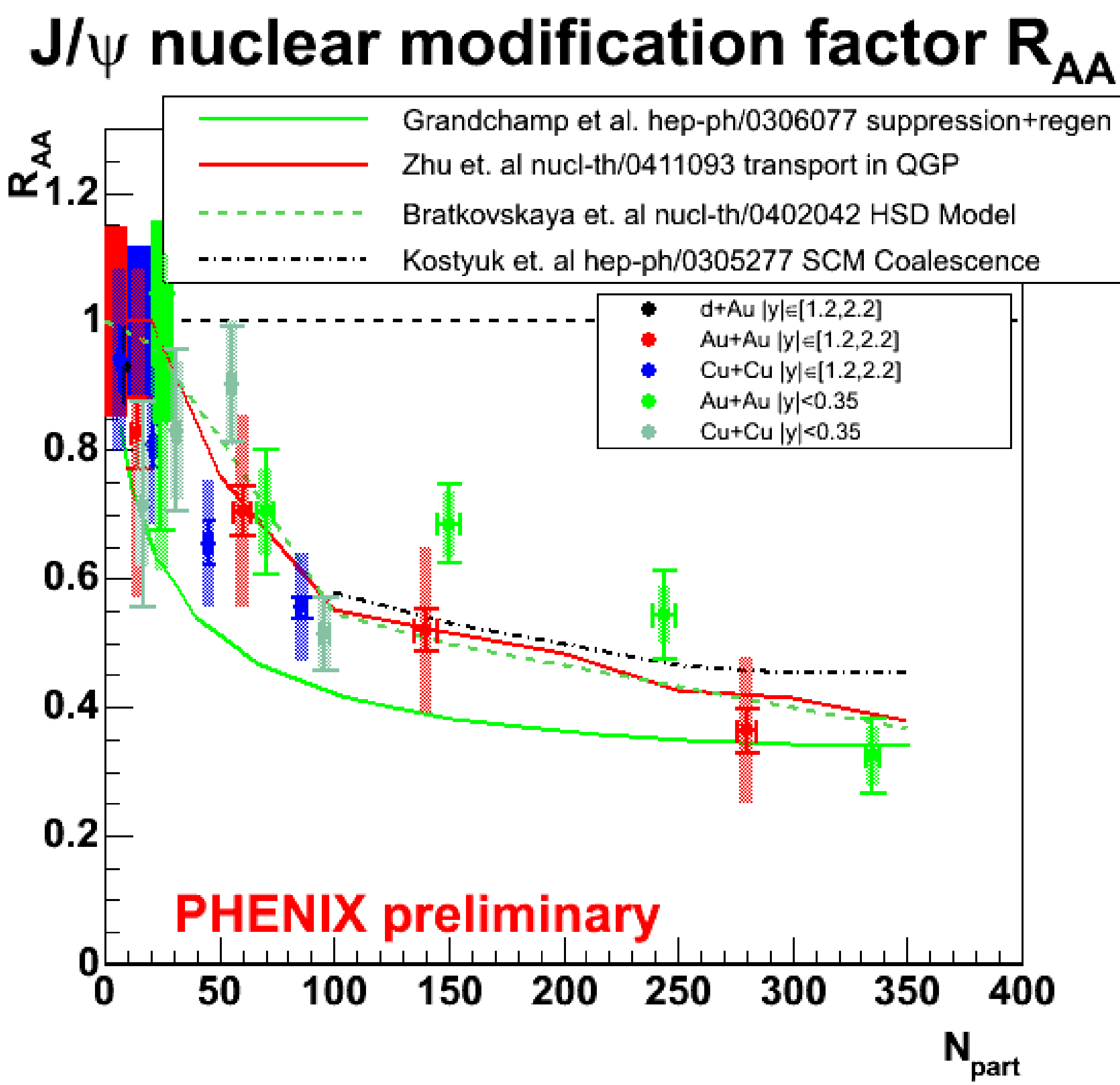
- Charm flows, but not as strong as light mesons.
- Drop of the flow strength at high p_T. Is this due to b-quark contribution?
- The data favors the model that charm quark itself flows at low p_T.
- Charm flow supports high parton density and strong coupling in the matter. It is not a weakly coupled gas.

Hot #3--(thermal?) photons



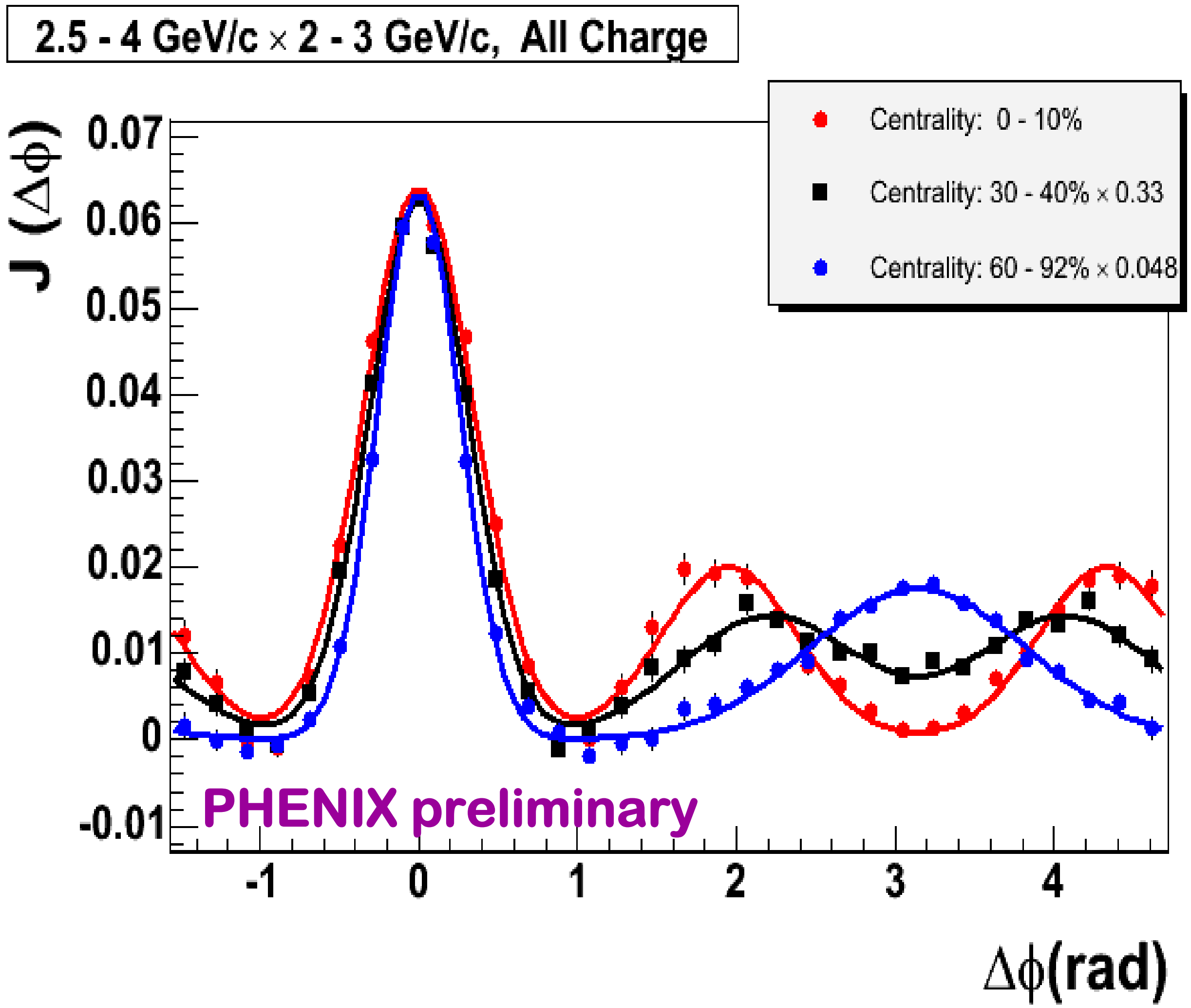
- The first promising result of direct photon measurement at low p_T from low-mass electron pair analysis.
- Are these thermal photons? The rate is above pQCD calculation. The method can be used in *p+p* collisions.
- If it is due to thermal radiation, the data can provide the first direct measurement of the initial temperature of the matter.
- T_0^{max} ~ 500-600 MeV !?
  T_0^{ave} ~ 300-400 MeV !?

Hot#4--melt J/ψ and regenerate it?



- J/ψ's are clearly suppressed beyond the cold nuclear matter effect
- The preliminary data are consistent with the predicted suppression + re-generation at the energy density of RHIC collisions.
- Can be tested by v_2(J/ψ)?

Hot#5—Away-side Jet Hole

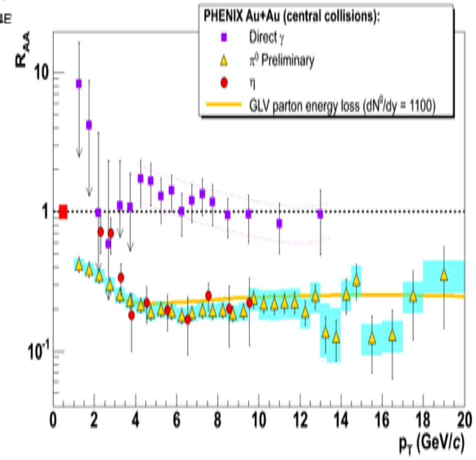


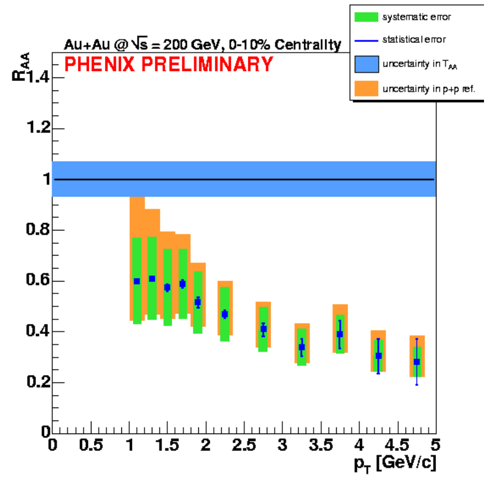
- The shapes of jets are modified by the matter.
  - Mach cone?
  - Cerenkov?
- Can the properties of the matter be measured from the shape?
  - Sound velocity
  - Di-electric constant
- Di-jet tomography is a powerful tool to probe the matter

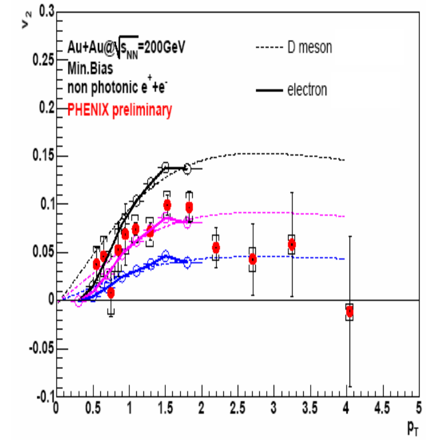
All Together Now:

STONY BROOK
STATE UNIVERSITY OF NEW YORK

PHENIX







The matter is dense

The matter is strongly coupled

We are now working with the theory community to extract the properties of the matter

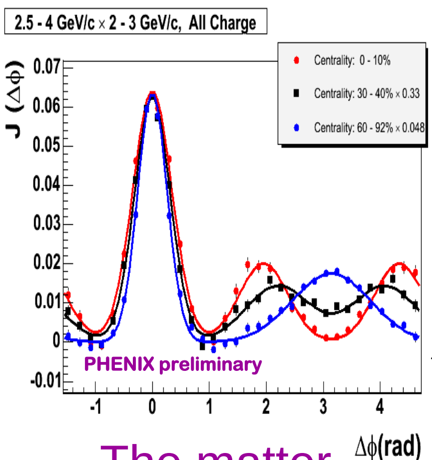
ε > 15 GeV/fm^3

dN_g/dy > 1100

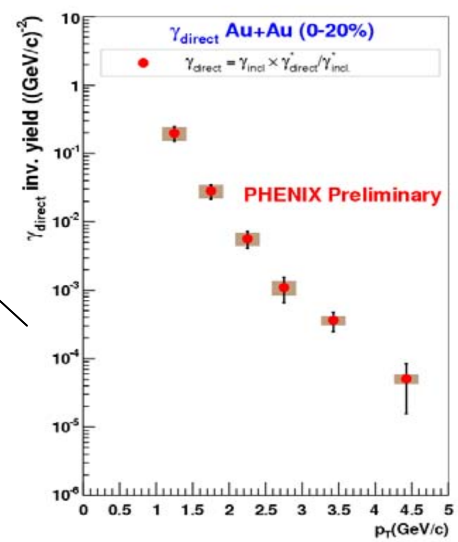
T_{ave} = 300 - 400 MeV (?)

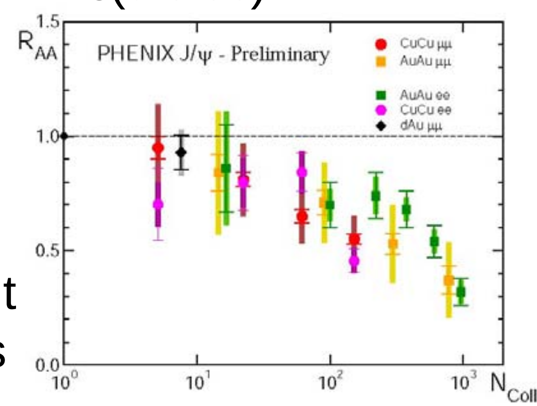
Vs = ?

ε(dielec) = ?



The matter modifies jets





The matter may melt but regenerate J/ψ's

The matter is hot